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EFFECTS OF ASCENT TRAJECTORY MODE
AND TANK DISPOSAL METHOD ON
SHUTTLE PAYLOAD ACCOMMODATION

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16. ABSTRACT

The capability of the Space Shuttle to deliver payloads of a given weight and length to the desired orbital altitude can be significantly affected by the trajectories and operational modes used for the Shuttle mission. This report documents an investigation of how Shuttle payload accommodation capability is affected by
(1) external tank disposal by retro-rocket versus passive tank drop and
(2) targeting the main engine burn for high apogee (direct insertion) versus the baseline parking-orbit ascent method. Missions launched from Eastern Test Range were investigated over a range of orbit altitudes to determine tank disposal requirements including footprint dispersions and alternate impact locations, performance, and Orbital Maneuvering System requirements. Passive tank drop, which is known to be superior to retro disposal from a Shuttle system standpoint, somewhat surprisingly proved to be advantageous from a payload accommodation standpoint also. Direct insertion is shown to be a means of accommodating long payloads at higher altitudes than permitted by the baseline ascent method; however, direct insertion requires disposal of the tank in the Pacific rather than the Indian Ocean. It is recommended that direct insertion be considered a viable Shuttle ascent mode, but because of the preferability of Indian Ocean disposal and the desire for standardization of mission profiles, its use should be restricted to those payloads which cannot be accommodated by the baseline ascent mode.

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I. INTRODUCTION

When the baseline concept for disposal of the Space Shuttle external tank was changed from a retro-rocket deboost to a passive tank drop, a concern was raised that flexibility to accommodate certain payloads and missions had been reduced or lost. Of particular concern were missions having long payloads (greater that 47.7 feet) which leave no room in the payload bay to add OMS fuel kits, yet which have altitude requirements significantly above 100 N.M. and thus may need to use the OMS kits. Examples of such missions include the Large Space Observatory, some configurations of the Sortie Lab, and possibly the Large Space Telescopes.

Before the disposal concept was changed, a technique for accommodating these missions called "direct insertion" was suggested but not thoroughly investigated. Direct insertion calls for targeting the main engine burn for a trajectory with apogee at the final desired mission altitude instead of targeting to a 100 N.M. parking orbit, thereby reducing the OMS requirements at the expense of performance delivered by the main engines. Flexibility of passive disposal to accommodate the above missions was in question in two respects: (1) the passive disposal concept requires more OMS propellant to achieve orbit than does the retro concept, hence the OMS kits would be needed at a lower mission altitude for passive disposal, and (2) direct insertion might not be usable for the passive disposal concept because of tank targeting problems. The study reported herein was undertaken to investigate these concerns.

The four fundamental high-altitude cases which were investigated and compared are illustrated in Figure 1. These four cases comprise the combinations of the two disposal modes (retro and passive OMS-to-orbit) and the two ascent modes (baseline with 100 N.M. parking orbit and direct ascent). Each case has been analyzed in detail from a flight mechanics viewpoint for launches from Eastern Test Range (ETR) at KSC, to determine the tank descent characteristics, location of the nominal impact zone, dispersions of the impact point caused by anomalies, retro-rocket size requirements where applicable, ascent performance of the main engine system, performance of the OMS burns, and the OMS kit requirements which lead to payload volume constraints.

Contrary to some initial expectations, it was found that the retro disposal concept provided only a negligible advantage in payload accommodation flexibility, yet was more complex operationally than passive OMS-to-orbit disposal. Therefore it is concluded that there would be no advantage to reopening the retro disposal issue. Using passive OMS-to-orbit disposal, it was found that direct insertion could significantly raise the minimum altitude at which OMS kits would be required, when compared with the baseline parking-orbit ascent method, hence

FIGURE 1

Desired Final Orbit Altitude = h
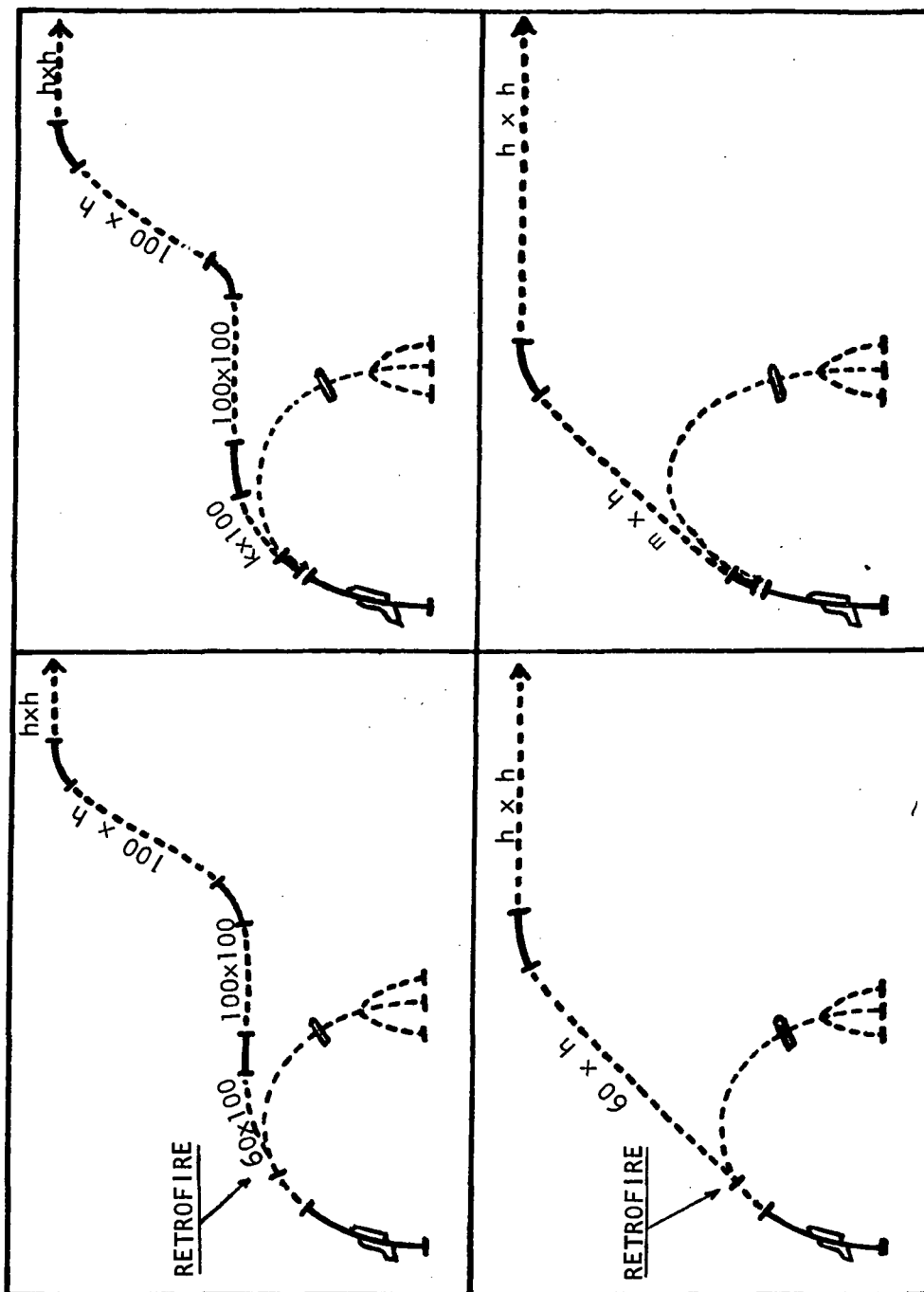
obtaining more payload accommodation flexibility. However, for direct injection to altitudes greater than about 200 N.M., performance losses incurred in targeting the tank for disposal in the Inidan Ocean force the use of an alternate disposal area in the Pacific Ocean. Pacific Ocean disposal, while feasible flight-mechanically, would appear to require tank impact in a region of higher ship and airplane density than would Indian Ocean disposal. It is recommended that direct insertion be considered as a technique for extending the altitude-volume constraints on Shuttle payload accommodation, to be used only for those particular payloads which require it.

The study is reported in two main parts: (1) the descent analysis, which includes retro-rocket sizing, passive tank targeting, footprint dispersions, and disposal site location, and (2) the ascent analysis, which includes performance analysis, OMS requirements, and payload weight-volume-altitude tradeoffs. Conclusions of the analysis follow each main section.

II. E. T. Disposal For Direct Injection Into High Apogee Orbits

During the time that retro from orbit was the baseline method for
E. T. disposal, study by organizations concerned with tank disposal
was concentrated on the Shuttle design ascent orbit of 50 x 100 N.M.
While the possibility of direct injection into orbits having apogees
higher than the design altitude of 100 N.M. had been mentioned, no
reported extensive investigations into the tank disposal problem for
this type orbit have been found. Prior to undertaking the work re-
ported here, S&E-AERO-G had investigated retro rocket tank disposal
for the baseline 50 x 100 N.M. orbit only (references 1 and 2). Passive
tank disposal in the Indian Ocean for the present baseline method of
OMS-to -orbit (OTO) had also been investigated by this organization.
No published documentation of this work was made, but the results were
presented orally to appropriate management. Personnel at JSC had
generated some data concerning tank disposal by retro rocket from
orbits having apogees between 100 and 1000 N.M. (references 3 and 4).
They concluded that for E.T.R. launch to a perigee injection altitude
of 50 N.M., Indian Ocean tank disposal would require very high retro
velocities for the higher apogee orbits. The suggestion was made that
retro velocity requirements for these high apogee orbits would be
considerably less if tank disposal were made in the Pacific rather than
the Indian Ocean. The nominal feasibility of using a 300 ft/sec retro
motor for Pacific Ocean disposal was demonstrated by tank entry
trajectories. No attempt was made to fix a nominal geographic tank im-
pact point for these trajectories, so the location of the impact point
changed as the apogee altitude of the orbit from which disposal was
made varied. Since this was sufficient preliminary data to prove the
point that was being made, no impact dispersion analysis was made, and
the need for this analysis was emphasized if Pacific Ocean disposal was
to be pursued further.

The study reported here was intended to expand on this background and
provide an overall perspective of the tank disposal problem associated
with E.T.R. direct launch to high apogee orbits. Data was generated
to encompass the total span of apogee altitudes from 100 to 1000 N.M.,
considering both retro motor and passive tank disposal, and considering
both the Indian and Pacific Oceans as possible disposal areas. To
this end three tasks were undertaken. They were:

(1) Determine the retro velocity requirements for Indian Ocean dis-
posal after E.T.R. launch and perigee injection for orbits having
perigee at 60 N.M., and apogees ranging from 100 to 1000 N.M. The 60
N.M. perigee altitude was used because this was the injection altitude
being considered at the time retro rocket tank disposal was replaced
by OMS to orbit as baseline for the Shuttle design.

(2) For the same range of orbits, and for a fixed geographic impact point and disposal area, determine the retro velocity requirements for Pacific Ocean disposal and the impact dispersions associated with these retro velocity requirements.

(3) Determine the main engine cutoff (MECO) conditions which would allow passive tank disposal at the same geographic point in the Pacific Ocean as was used for retro rocket disposal, and the impact dispersions associated with these MECO conditions.

The data from these three tasks, together with that previously obtained for passive tank disposal in the Indian Ocean, form the basis of the results reported here. For disposal by retro motor, the primary concern was defining the range of possible orbit apogee altitudes over which a given retro motor size could be utilized. The data for passive tank disposal was included so that this method could be compared with retro rocket as a means of tank disposal for high apogee orbits.

A. Method of Analysis

Because of the large amount of computational work involved in investigating tank disposal by retro from orbit, the following constraints were placed on data generation for this study in order to keep the work load within a reasonable bound.

1. Only ETR launch to orbits of 28.5°inclination were actively investigated, but the data obtained is applicable with very minor modifications to the other orbit inclinations being considered for ETR launch.

2. No dispersion analysis was made for Indian Ocean disposal by retro rocket; the retro velocity requirements only were determined.

3. For Pacific Ocean disposal by retro rocket, three orbits were chosen for intensive investigation of retro velocity requirements and impact dispersions. These are 60 x 330 N.M., 60 x 660 N.M., and 60 x 990 N.M. These were chosen because they span the range of orbits being investigated, and the data obtained, either directly or by extrapolation, should provide the overall perspective being sought.

Other information concerning the method of analysis is contained in Table 1.

B. Disposal Areas

Figure 2 shows a map of the Indian Ocean with an overlay of projected shipping density for the year 1980 (reference 5). This map is taken from reference 2. The debris track labeled "mission 1" was contained

TABLE 1
METHOD OF ANALYSIS

o 3-D BALLISTIC TRAJECTORIES UTILIZING:

  -- FISHER ELLIPSOIDAL EARTH MODEL

  -- U. S. 62 STANDARD ATMOSPHERE

  -- TUMBLING TANK, CONSTANT BALLISTIC PARAMETER 29 PSF

o INTACT IMPACT DISPERSIONS COMPUTED AS RSS OF:

  -- RETRO DISPOSAL 3-SIGMA ERRORS

    (1) MECO NAVIGATIONAL ERRORS:

         VELOCITY $\pm$ 12.18 FT/SEC

         PATH ANGLE $\pm$ .039 DEG

         ALTITUDE $\pm$ 3596 FT

    (2) RETRO ERRORS:

         $\Delta V \pm 5\%$

         TIME $\pm$ 15 SEC

         INTEGRATED THRUSTING POINTING $\pm$ 25 DEG

    (3) AERODYNAMICS:

         DRAG COEFFICIENT $\pm$ 10%

  -- PASSIVE DISPOSAL 3-SIGMA ERRORS

    (1) MECO NAVIGATIONAL ERRORS:

         VELOCITY $\pm$ 12.18 FT/SEC

         PATH ANGLE $\pm$ .039 DEG

         ALTITUDE $\pm$ 3596 FT

    (2) AERODYNAMICS:

         + 50% DENSITY VARIATION

         - 25% DENSITY VARIATION

FIGURE 2
ETR LAUNCH – PRE-INSERTION ET DROP
INTO INDIAN OCEAN IMPACT AREAS

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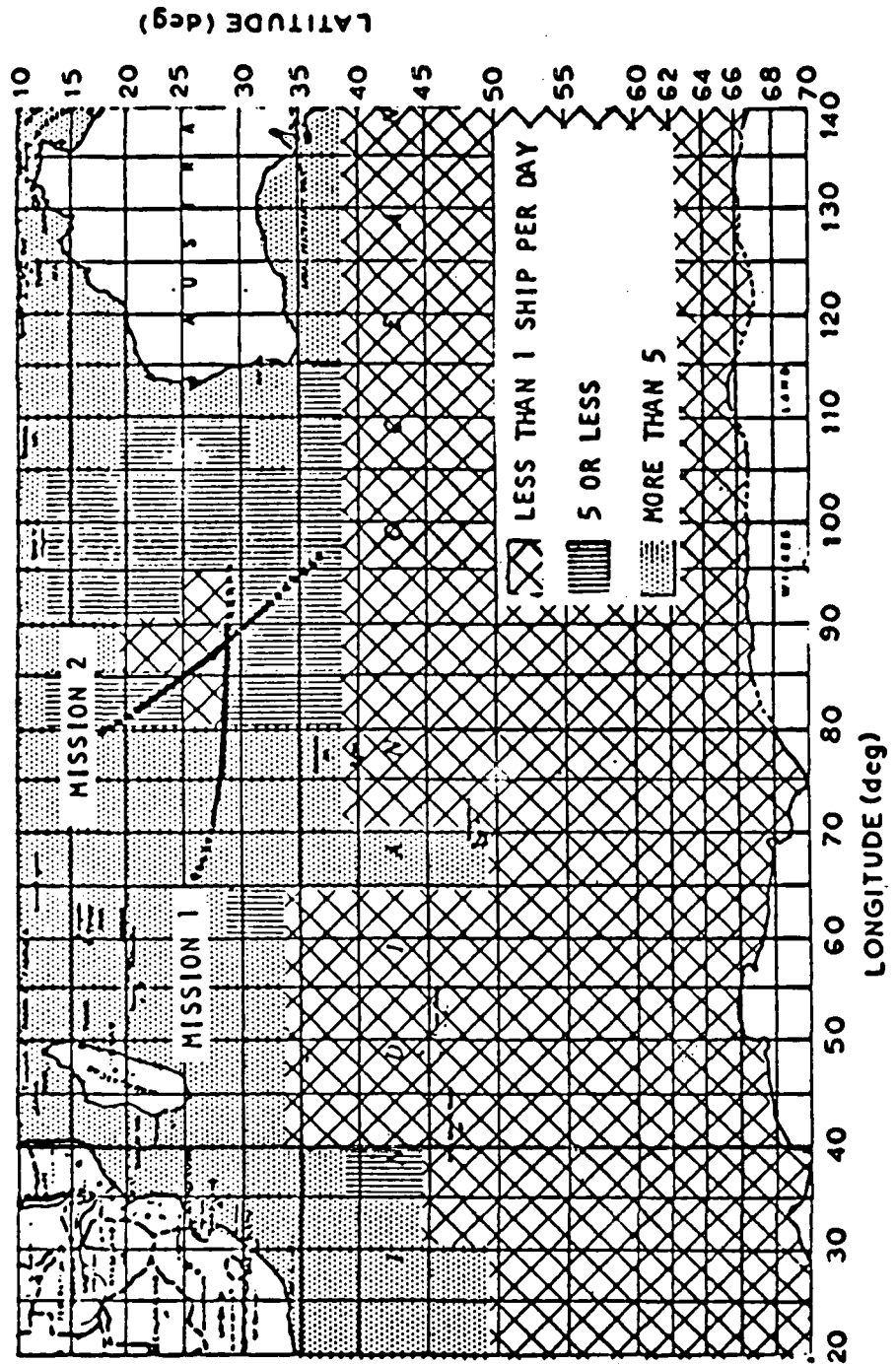
in that reference. It shows where the disposal track will lie when the
nominal impact point for a due east launch from ETR is at 80 degrees
east longitude.   The solid line represents the intact impact dispersion,
and the dotted extensions represent a computed breakup dispersion added
on.   The line labeled "mission 2" shows where the disposal track will
be if the launch is to a 55 degree inclination orbit and the same range
angle from injection to impact is maintained as in the case of the due
east launch. The disposal tracks for any inclination between 28.5
degrees and 55 degree orbits would be in the area spanned by these two
tracks.   These tracks are approximately 1800 N.M. long, and 660 N.M.
of this is breakup dispersion. This preliminary breakup dispersion
length was based on an assumed breakup altitude and assumed range of
ballistic coefficients of the pieces. A detailed analysis is now in
progress to accurately define the footprint of debris spread after
breakup for the ET, but will require a number of months to complete.
In the absence of those results we have adopted a constraint based on
the breakup analysis of reference 2. For our studies of passive tank
disposal in the Indian Ocean, in order to insure that the disposal
would be in the area shown on Figure 2, a conservative constraint of
1000 N.M. total intact dispersion was defined. Only those MECO
conditions for which the intact dispersion was 1000 N.M. or less were
considered acceptable.

Figure 3 shows the Pacific Ocean disposal area for this study. The
nominal impact point for the 28.5 degree inclination orbit was fixed
at 135 degrees west longitude. This point is about half way between
Hawaii and the Lower California coast. The length of allowed disposal
track for this orbit was fixed to allow a 200 N.M. safety zone from
these two land areas. The range angle from injection is such that
results found in studying the 28.5 degree inclination orbit can be
applied to other orbits with ETR launch as well with an open water
disposal track assured. The line of dots shows how the nominal impact
point will vary with orbit inclination, and the area through which the
disposal track will sweep is shown. Note that the length of disposal
track is approximately 1800 N.M. long, the same length as the tracks
shown for Indian Ocean disposal on Figure 2. Because of this fact and
the reason previously stated regarding breakup dispersion length, we
adopted the same intact dispersion length constraint for Pacific Ocean
disposal as for Indian Ocean disposal. For both retro from orbit and
passive disposal, 1000 N.M. intact dispersion was considered a limit
defining acceptability.

Figure 4 shows the same area as Figure 3 with a shipping density overlay.
If Figure 4 is compared with Figure 2, one significant difference can
be noted. The nominal impact point at 80 degrees east longitude in
Figure 1 was set when tank disposal was first being investigated,
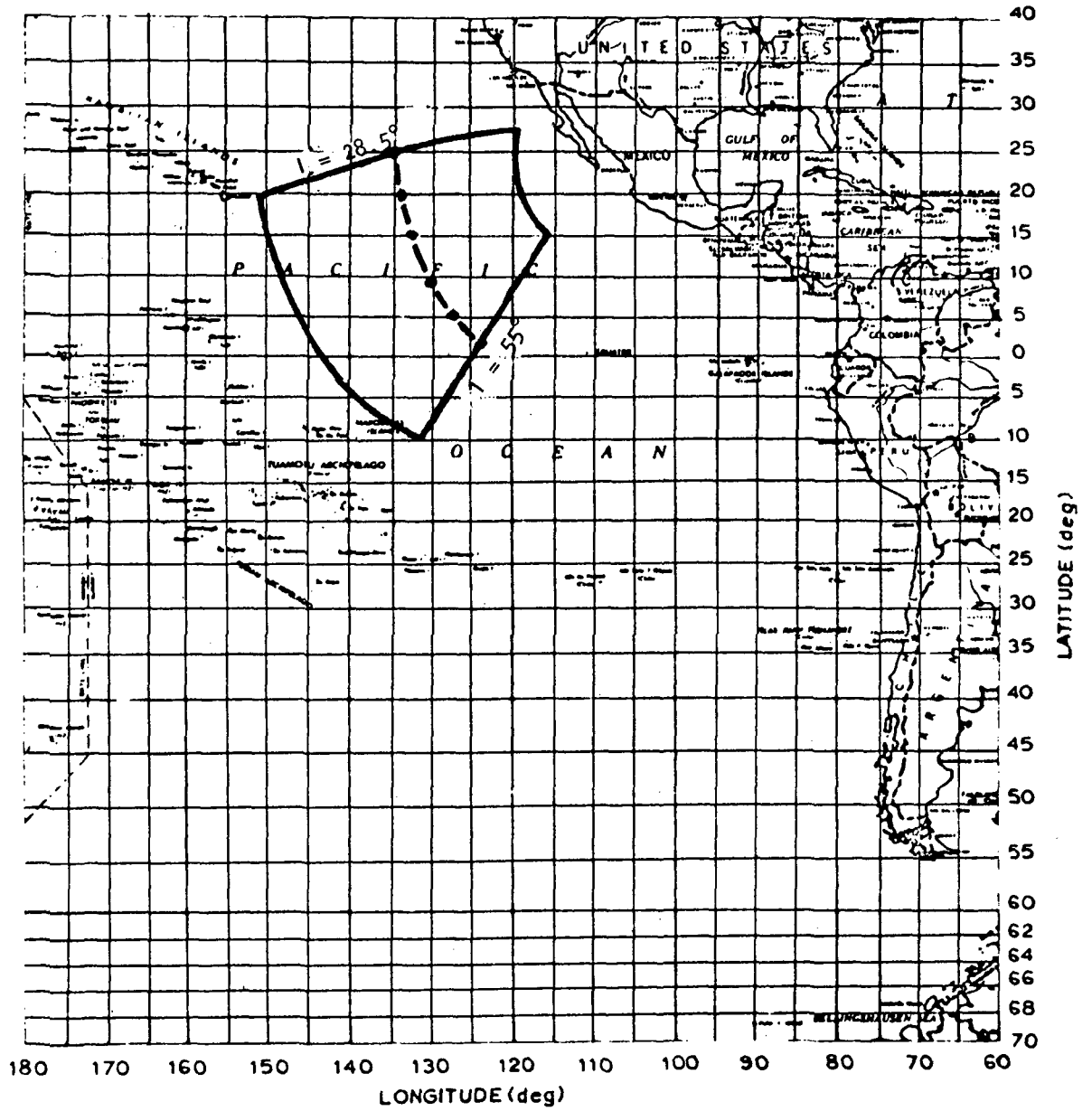before knowledge of what despersion length would have to be considered,
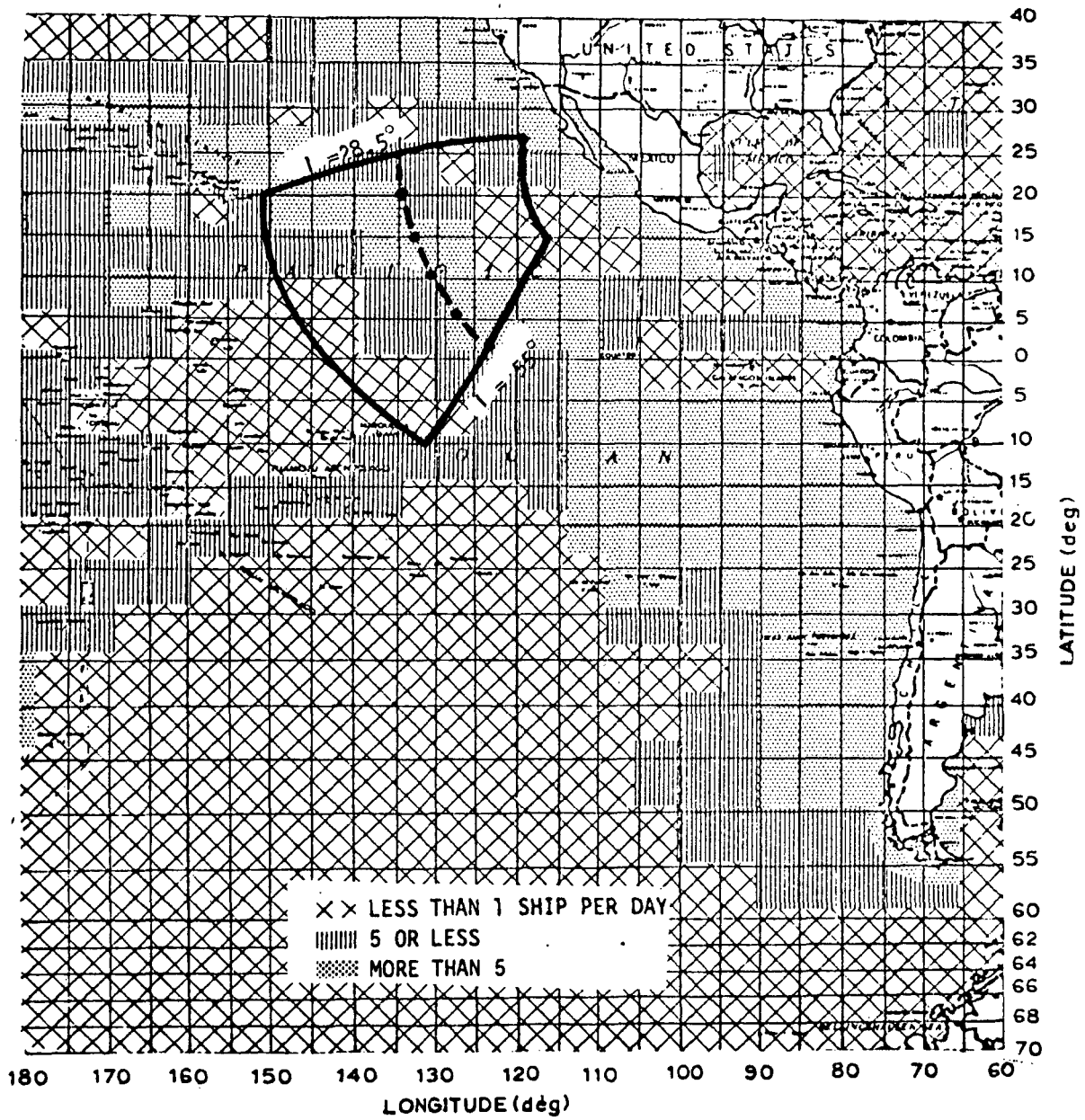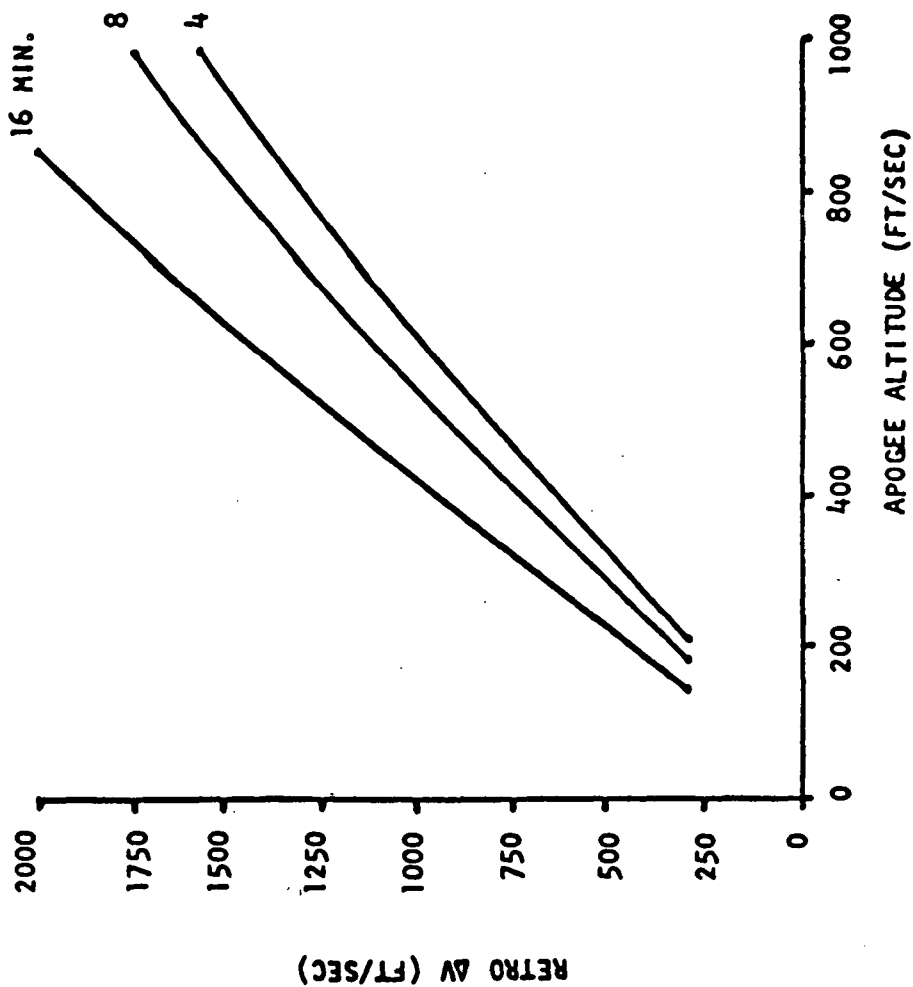
FIGURE 3

FIGURE 3

FIGURE 4

FIGURE 5

RETRO ΔV. REQUIREMENTS FOR INDIAN OCEAN DISPOSAL AS FUNCTION OF APOGEE ALTITUDE
PERIGEE INJECTION AT 60 N. M. - - ETR LAUNCH

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and without information on shipping density. It was set approximately halfway between Madagascar and Australia to insure minimum probability of land impact. Figure 2 shows that if the nominal impact point is moved East to about 90 degrees East longitude, then the same length impact footprint would be almost totally in a relatively low shipping density area, and an adequate safety margin from land impact on Australia maintained. If this same shift in range angle is applied to the other orbit inclinations, then almost all the Indian Ocean disposal area will lie in a relatively low shipping area. While our passive disposal results for Indian Ocean disposal are based on the assumption that the disposal area will be as shown in Figure 2, this shift to obtain lower shipping impact probability can be made with very little change in either the MECO conditions or dispersions. For computing the retro requirements for Indian Ocean disposal from high apogee orbits we used 90 degrees East longitude as the nominal impact point for the due East inclination. Figure 4 shows that no shift of this type is possible for Pacific Ocean disposal and that higher shipping impact probability will exist for Pacific Ocean disposal compared to Indian Ocean disposal. Also, while no aircraft density data is available, it would be expected that the Pacific Ocean disposal region would have a higher aircraft density than the Indian Ocean disposal region.

C. Retro Velocity Requirements for Indian Ocean Disposal

Figure 5 shows the retro velocity requirements that were computed for Indian Ocean disposal. The requirements for three successive times of retro fire after injection are shown. Four minutes after injection has been defined as a minimum time to dump fuel and complete preparations for retro fire, so the four minute curve represents a most optimistic retro requirement. If dispersion analysis along the four minute curve should yield unacceptable dispersions, then a later retro time, and corresponding higher retro velocity would be required. It can be seen that even for the four minutes after injection retro time, a 300 FT/SEC retro motor would be limited to use in orbits having apogee no higher than slightly over 200 N.M., and for higher apogee orbits the retro velocity requirement increases drastically.

D. Operational Constraint In Retro Rocket Disposal

Before displaying any specific data found for Pacific Ocean disposal by retro rocket, it is necessary to discuss a point which is central to the conclusions made from that data.

As stated earlier in this section, it was intended in this study to define the magnitude of retro velocity requirements for Indian or Pacific Ocean disposal over a large span of orbits. Another goal more

in keeping with the overall intent of the study was to establish what limitations would exist on the range of orbits for which any particular retro size could be utilized. In assessing data for this purpose we have assumed that a recognized operational constraint of retro rocket disposal would be observed.

This operational constraint dictates that any given retro size be utilized at that time in orbit when it is equal to the required retro velocity to impact a fixed disposal target point. The reason it would not be used at a time when it is less than the required retro velocity is obvious ; a downrange impact error would result. The reason it would not be used at a time when it is greater than the required retro velocity is not obvious. Simply stated, the reason is this: while it is always physically possible to impact the disposal target when the given retro size is greater than required, the impact dispersion due to retro fire misalignment will be much greater than if the given retro size is used when it is equal to the required retro velocity. Minimum dispersion due to retro fire misalignment can be obtained only if a given retro size is used at exactly that time in orbit when it is equal to the required retro velocity to impact a given disposal target. In effect, one must operate on the curve of minimum required retro velocity versus time after injection for any orbit to obtain minimum dispersion due to retro fire misalignment. A detailed discussion of this operational constraint along with examples of the gross disposal footprint dispersion that results if it is not observed is contained in reference 2.

The significance this operational constraint has in defining the range of orbits for which any given retro size can be utilized for either Indian or Pacific Ocean disposal is illustrated by Figure 6.

Figure 6 shows the general shape of the curves defining the required retro velocity as a function of time after insertion into orbit for both Indian Ocean and Pacific Ocean disposal. The difference in the shape of the curves for the two cases is due to the difference in range angle from injection to the disposal points in the two oceans. For Indian Ocean disposal, retro requirements are a minimum at injection and continually increase as time in orbit increases. For Pacific Ocean disposal, retro requirements are high at injection, decrease with time after injection to some minimum value prior to apogee, then increase. Once this minimum retro velocity requirement point is passed, then the curves for Pacific Ocean disposal are similar to those for Indian Ocean disposal.

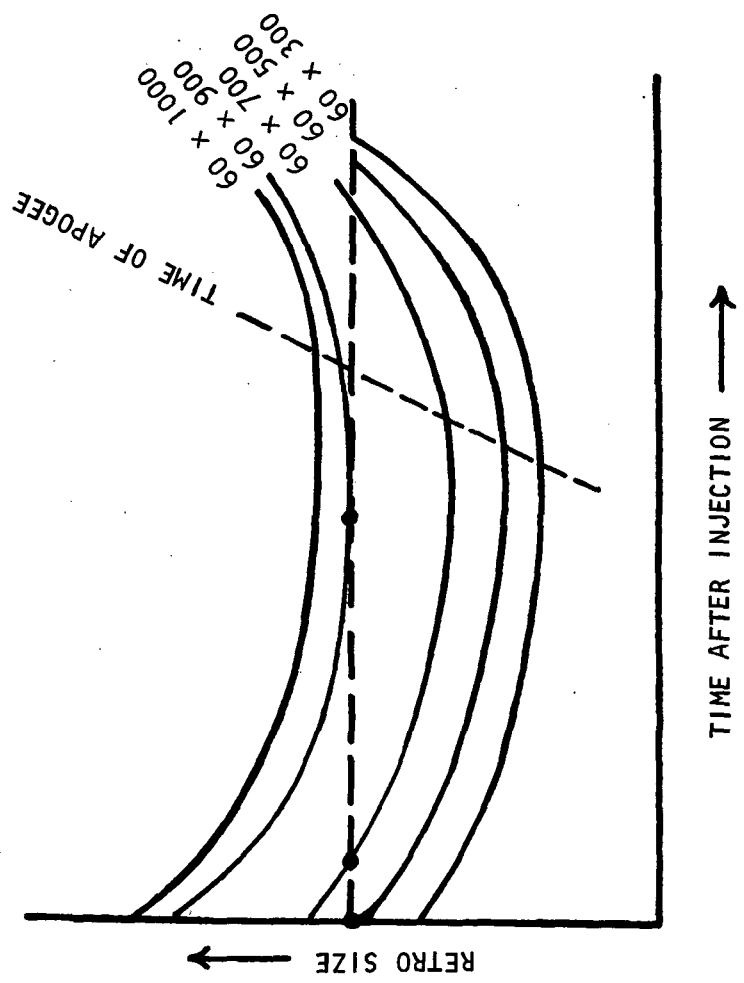For Indian Ocean disposal, if the retro velocity available were that defined by the dashed line, then the maximum apogee orbit for which it could be used would be 60 x 600 N.M. This retro size could also be used for any other orbit having apogee less than 600 N.M., with minimum dispersion due to retro fire misalignment, simply by waiting until that

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FIGURE 6

PACIFIC OCEAN DISPOSAL

INDIAN OCEAN DISPOSAL

14
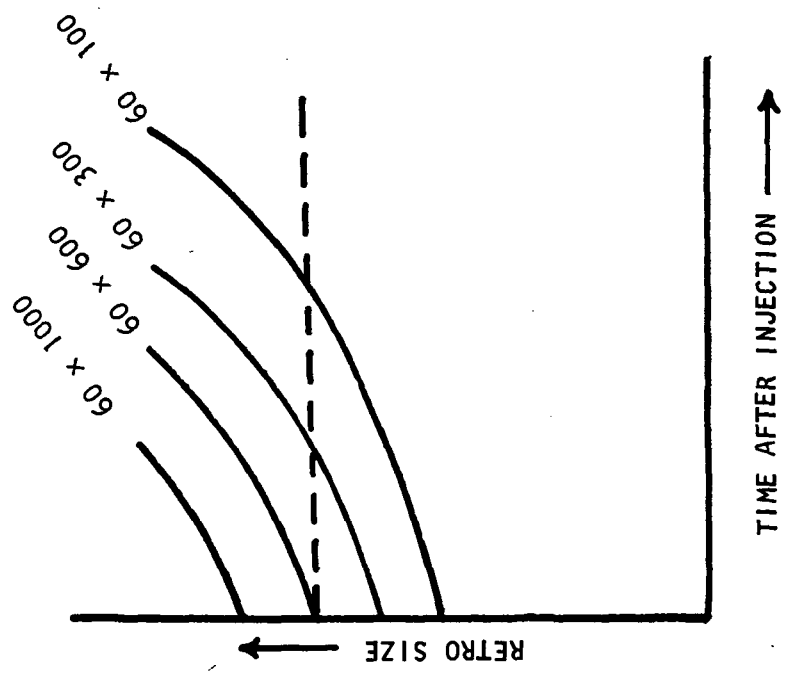
time in orbit when it is the required retro velocity. For Indian Ocean disposal by retro motor, there is a maximum orbit apogee value for which a given retro size can be used, but no minimum apogee value.

For Pacific Ocean disposal, a different situation exists. If the retro size is that illustrated by the dashed line then there is again a maximum orbit apogee for which that retro size could be used. In the case it would be 900 N.M., and there is only one time point in the 60 x 900 N.M. orbit when this retro size could be used. At any other time it is less than the required retro velocity. For orbits with apogee values close to 900 N.M., there are two times where this retro value could be used, one before apogee and one after apogee. This is the case for the 60 x 700 and 60 x 500 N.M. curves. For orbits with apogee values more removed from 900 N.M., there is only one time point when this retro size can be used, and it occurs after apogee. The curve for 60 x 300 N.M. illustrates this case.

It can be seen from this illustration that use of a given retro size for a range of orbit apogees will have an operational complexity for Pacific Ocean disposal that doesn't exist for Indian Ocean disposal. Once a retro size is specified, and consequently a maximum altitude orbit for which it can be used, then this retro size can be used for all orbit altitude values less than this maximum only if retro fire can occur after apogee. This would mean, for those cases where this is required, that one full orbit would be devoted to tank disposal, and circularization would have to be done at the second passing of apogee rather than the first. Another possibility for accommodating a greater range of orbits for a fixed retro size while avoiding the need to retro-fire after apogee would be to retrofire out of the flight plane in order to reduce the inplane component of retro velocity to the required value.

In assessing the date found for Pacific Ocean disposal we have assumed that either the extra orbit or the out of plane retrofire would introduce unacceptable operational complexity. The result of this assumption is that for Pacific Ocean disposal by retro motor, there is a maximum orbit apogee value for which a given retro size can be used, and there is also a minimum apogee value for which that size can be used.

E. Retro Velocity Requirements for Pacific Ocean Disposal

Figure 7 shows the results found for Pacific Ocean disposal by retro rocket. The required retro velocity as a function of time after injection is shown for the three orbits investigated as solid lines. It is immediately obvious that the retro size requirements for Pacific Ocean disposal for the range of orbits considered are much smaller than for Indian Ocean disposal. As expected, the data obtained from examining these three orbits is sufficient to deduce information pertaining to the

FIGURE 7
DUE EAST LAUNCH FROM ETR
TANK DISPOSAL AT 135° W LONGITUDE IN PACIFIC

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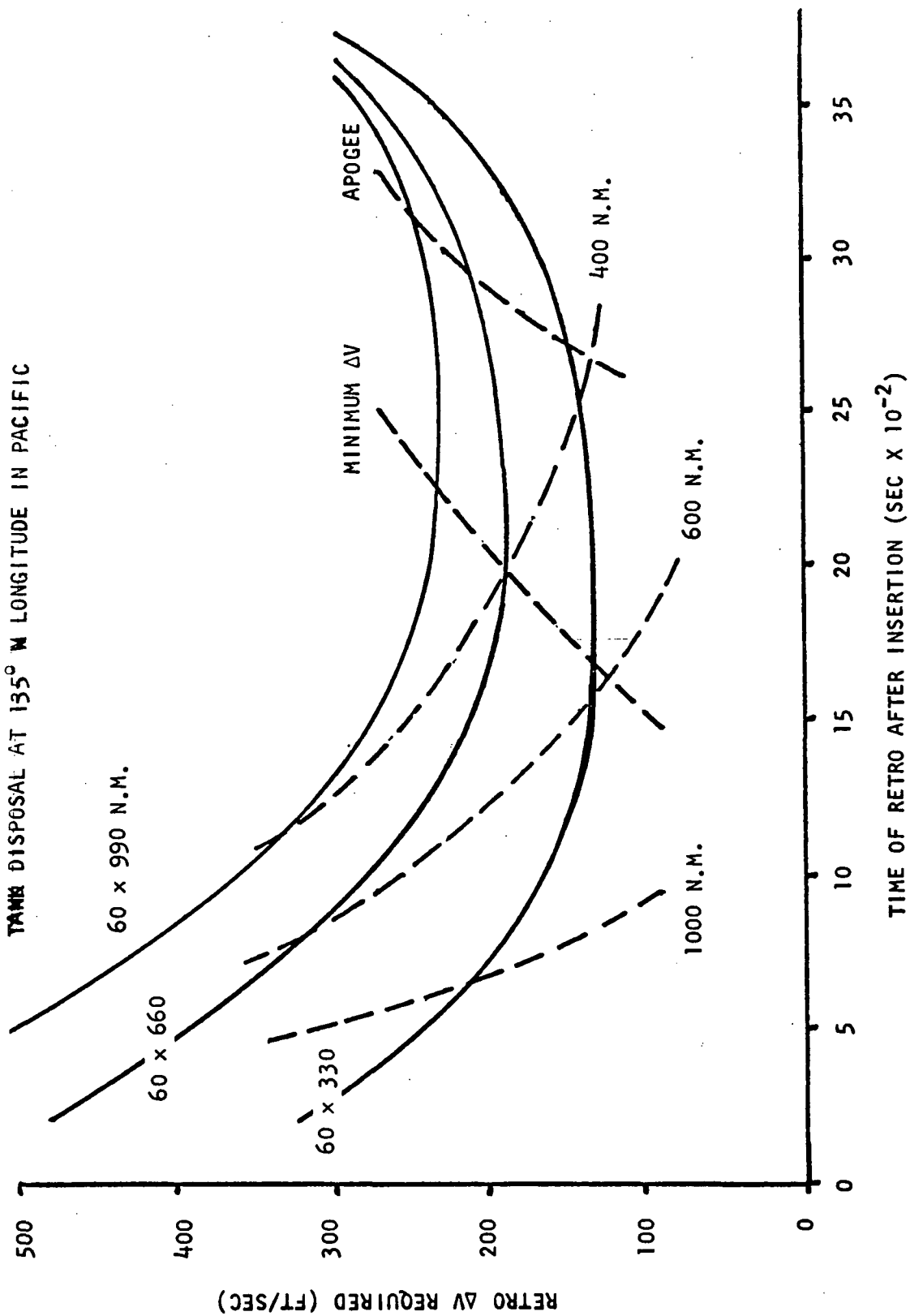
total span of orbits considered in the study. The curves are of such a regular nature that those for any orbits other than those shown can be inserted visually.

Dashed lines representing the time of apogee and the time of minimum retro velocity requirement have been imposed on the curves. It can be seen that the minimum retro velocity requirement occurs about 1000 seconds before apogee. Also imposed on the curves are dashed lines representing constant total intact impact dispersion, assuming, as stated before, exactly the required retro velocity is being used at any time.

Figure 7 can be used to define the range of orbits for which a given retro size can be utilized for Pacific Ocean disposal. We have assumed that retrofire must occur before apogee, and that intact dispersion must be limited to 1000 N.M. The effect of these two constraints on the range of orbits for which a given retro size can be used is illustrated by this example. If a retro size of 200 FT/SEC is available, then the maximum apogee altitude orbit for which it can be used is that orbit for which 200 FT/SEC is the minimum required retro velocity, approximately 60 x 700 N.M. For orbits having apogees higher than 700 N.M., 200 FT/SEC is less than the required retro velocity at all times. The minimum apogee altitude orbit for which the 200 FT/SEC retro size can be used is 60 x 330 N.M. For orbits having apogees less than 330 N.M., more than 1000 N.M. intact dispersion would result if the 200 FT/SEC motor were used at the time point before apogee when it is the required retro velocity.

In effect, the range of orbits over which a given retro size can be used is bounded and determined by the dashed line showing the minimum retro velocity requirement and the dashed line showing 1000 N.M. total intact impact dispersion. It can be seen also that these two dashed lines tend to converge for lower apogee altitude values, and it is evident that the smaller the retro sizes, the more constrained will be the range of orbits for which that retro size could be used.

F. Overall View of Retro Velocity Requirements

The data extracted from Figure 7 concerning the range of orbits for which a given retro size can be used for Pacific Ocean disposal has been combined with the data of Figure 5 concerning Indian Ocean disposal to form Figure 8. This figure shows the range of orbits for which a given retro size can be used for either Indian or Pacific Ocean disposal. It is obvious from examining Figure 8 that even considering both oceans for disposal, no reasonable value of retro size will give capability over the full range of orbits considered. If a 300 FT/SEC motor is available, it could be used for orbits having apogee values up to 200 N.M. with Indian Ocean disposal. It could also be used for orbits having apogee altitudes of 500 N.M. or greater with Pacific Ocean

FIGURE 8
DUE EAST LAUNCH FROM ETR

60 N. M. PERIGEE INJECTION
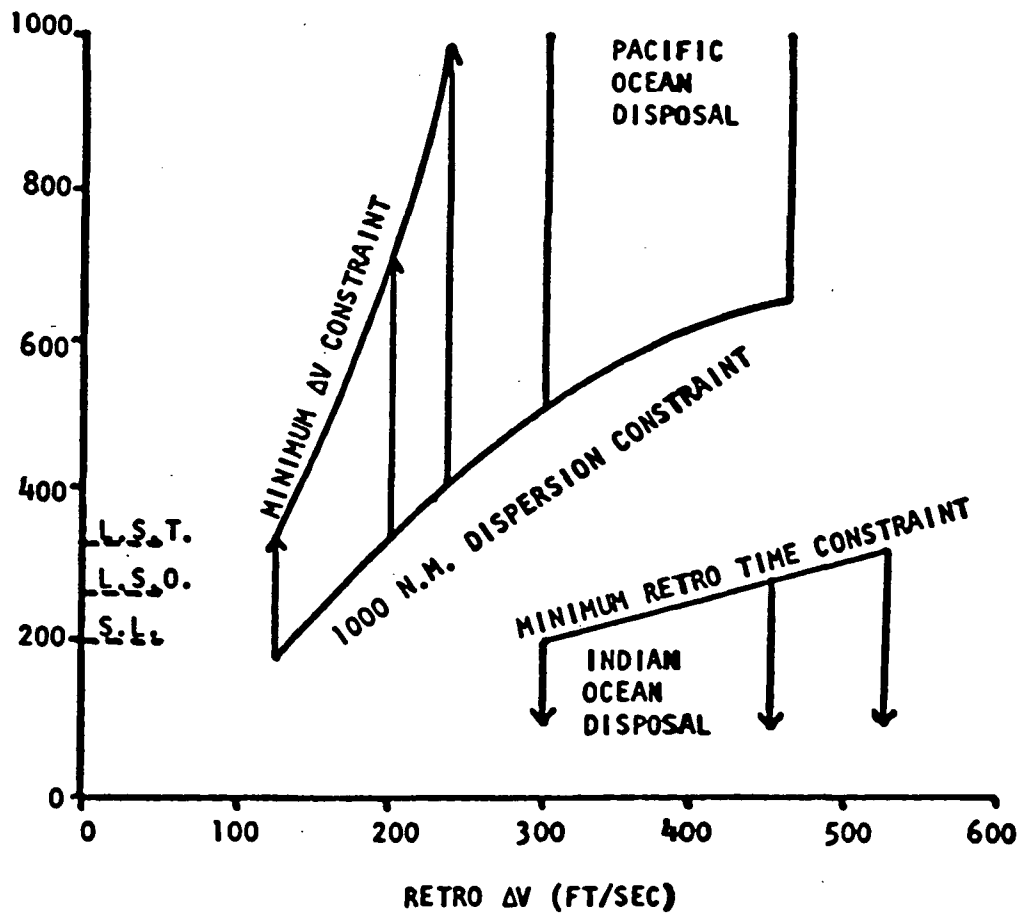
disposal, but for orbits with apogee altitudes between 200 and 500 N.M. it could not be used. If a particular mission model should lie in this range, then a very high retro velocity for Indian Ocean disposal would be needed, or smaller retro size with Pacific Ocean disposal could be used. It can also be seen from the figure that to have capability over the span from 200 to 500 N.M. with Pacific Ocean disposal, two retro sizes would be required. A retro size of 160 FT/SEC could be used for orbit apogees from 500 N.M. down to 270 N.M., but for capability between 270 and 200 N.M., a second smaller sized motor would be needed.

G. Use of Passive Disposal for Direct Injection Into High Apogee Orbits

Figure 9 gives data relating to passive tank disposal in the Indian Ocean after ETR launch. The MECO velocity and path angle combinations which impact the tank at the target point are shown for injection altitudes ranging from 50 to 65 N.M. Also shown are the intact impact dispersion and apogee altitude of the insertion orbit associated with the cutoff conditions for the 60 N.M. insertion altitude. It can be seen that the 1000 N.M. dispersion constraint defines the minimum path angle for cutoff and the resultant minimum apogee of the insertion orbit. It can also be seen that if higher apogees than the minimum for the insertion orbit are desired, one can move along the MECO curve to higher path angles and lower cutoff velocities. No problem with disposal will result because the dispersion will be less than 1000 N.M. However, the resultant lowered orbit energy at MECO has a detrimental effect on performance which will be discussed in the performance section of this report.

Figure 10 shows the MECO conditions at 60 N.M. with ETR launch which can be used for passive tank disposal in the Pacific Ocean, and the associated dispersion and insertion orbit apogees. While the dispersion and injection orbit apogee curves are similar in appearance to those for Indian Ocean disposal, note that the slope of the curve defining MECO is reversed from that for Indian Ocean disposal. The 1000 N.M. dispersion constraint is again defining the minimum apogee orbit of injection. However, moving along the MECO curve to obtain higher injection orbit apogees here requires higher velocity at MECO, and does not cause the detrimental lowered orbit energy effect seen for Indian Ocean disposal. The signigicance of this fact will be discussed in the performance section. It can be seen also that the 1000 N.M. dispersion constraint limits the lowest orbit apogee value for which passive disposal in the Pacific Ocean can be used to 200 N.M.

FIGURE 9

OMS-TO-ORBIT TARGETING

INDIAN OCEAN DISPOSAL

DUE EAST LAUNCH
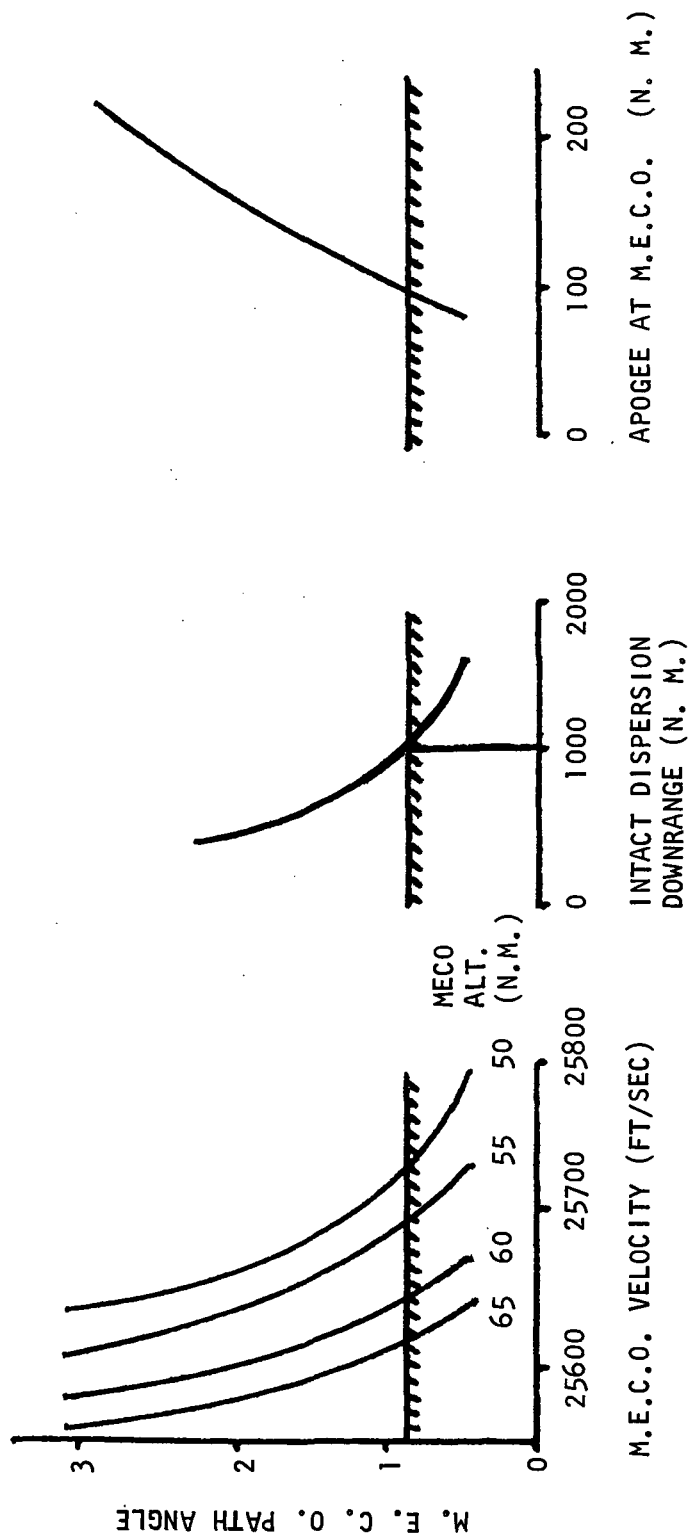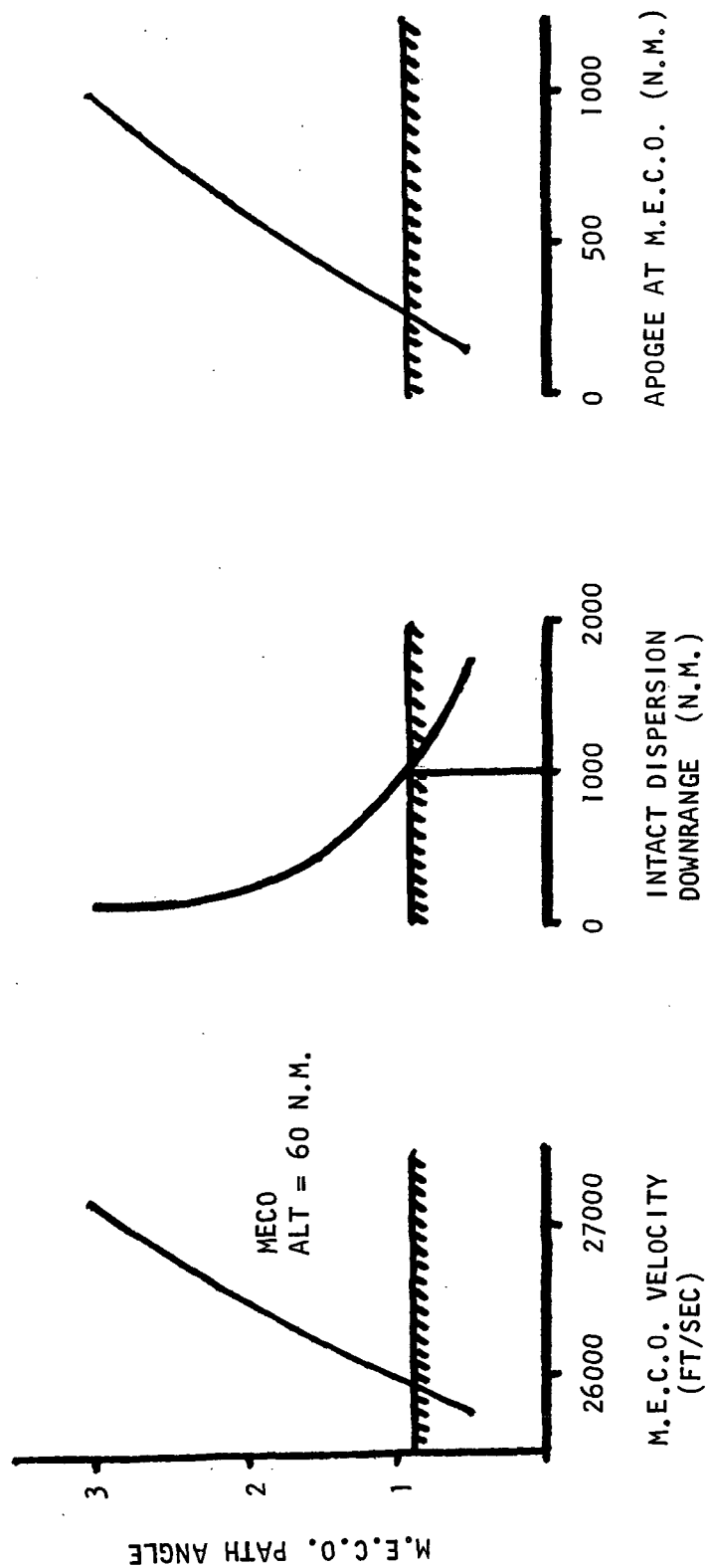
IMPACT POINT AT 80° EAST LONGITUDE

FIGURE 10

OMS-TO-ORBIT TARGETING

PACIFIC OCEAN DISPOSAL

DUE EAST LAUNCH

IMPACT POINT AT 135° WEST LONGITUDE

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H. Descent Analysis Conclusions

In assessing the tank disposal problem associated with direct injection into orbits having apogee higher than the Shuttle design altitude of 100 N.M., our analysis was primarily concerned with examining the feasibility of the use of retro rocket for disposal and defining the range of orbit apogee values over which a given retro size could be utilized, and providing data relating to the use of passive tank disposal so that this method could be compared to retro motor for disposal from these orbits.

1. Regarding disposal by retro rocket:

    a. For Indian Ocean disposal

        (1) A 300 FT/SEC retro motor could be utilized for orbit apogees no higher than 200 N.M.

        (2) For apogees higher than 200 N.M., retro velocity requirements increase significantly with increasing orbit apogee.

        (3) If a retro size is fixed, then this size determines the highest apogee value for which the motor can be utilized. There is no lower bound on the apogee value for which the motor could be used.

    b. For Pacific Ocean disposal

        (1) Pacific Ocean disposal has been found to be feasible with respect to flight mechanics.

        (2) In general, much lower values of retro rocket size would be required compared to Indian Ocean disposal.

        (3) A higher probability of ship impact will exist for Pacific Ocean disposal than for Indian Ocean disposal. There is also a possibility that high aircraft density will exist in the Pacific Ocean disposal area. This possibility should be investigated if Pacific Ocean disposal is used.

        (4) Although smaller retro sizes will be required than for Indian Ocean disposal, there will be both an upper and lower bound on the range of orbits for which a given size can be utilized. The smaller the retro size, the more constrained this range will be.

        (5) Choice of retro rocket size will be dependent on the range of apogee values encompassed by the mission model, and probably more than one retro size will be required.

(6) The lower bound on the value of orbit apogee for which a given retro size can be utilized can be avoided only by considering the operational complexities of:

(a) Use of an out of plane firing angle to reduce the in plane component of retro velocity to the desired value. In this case, a double angle error would have to be considered in determining dispersion due to retro fire misalignment.

(b) Wait until after orbit apogee to initiate retro fire. This would require devoting one full orbit to accomplishing tank disposal.

2. Regarding passive tank disposal:

a. Passive tank disposal in the Indian Ocean could be utilized for direct injection into orbits having apogee values up to 200 N.M. For apogee values greater than 200 N.M., performance considerations rule out the use of passive disposal in the Indian Ocean.

b. Passive disposal in the Pacific Ocean is feasible with respect to flight mechanics but the shipping and aircraft density aspects previously stated would have to be considered. Dispersion analysis indicates that passive tank disposal in the Pacific Ocean would be limited to orbits having apogee of 200 N.M. or greater.

III. Orbital Performance

In this section, the on-orbit performance for OMS-to-Orbit (OTO) is compared with the on-orbit performance for a system with a retro motor ET disposal system. Comparison is provided for the standard insertion technique in which main engine cutoff occurs in a low altitude transfer orbit and in which the orbiter circularizes in a 100 N.M. orbit for system checkout and navigation system update before transfering to the final operating orbit. Comparison is also provided for direct insertion in which main engine cutoff occurs in an orbit with the apogee equal to the altitude of the desired operating orbit.

The performance comparison is provided in the following sequence:

A. Study groundrules
B. Comparison of insertion conditions (main engine cutoff conditions)
C. Comparison of OMS ΔV requirements and net payload
D. Comparison of OMS propellant requirements
E. Summary performance comparison of insertion methods
F. Performance Analysis Conclusions

A. Study groundrules

The NAR 72-061 Shuttle Vehicle (January 1973) was used for the study. This vehicle has a retro motor for ET disposal. The effect of removing the retro motor was approximated by removing 4000 pounds from the baseline ET cutoff weight of 94,969 pounds.

The study was performed assuming a fixed liftoff weight and a common abort once around trajectory to provide maximum uniformity of ascent performance. For all cases, main engine cutoff occurred at 60 NM equatorial altitude into an orbit with 28.5° inclination. For the retro system, insertion occurred at perigee of the transfer orbit; for the OTO system, insertion occurred at targeting conditions yielding the desired ET impact point with acceptable dispersions as defined in the previous section.

B. Comparison of insertion conditions

In order to explain the performance shown later in the report, it is necessary to examine the energy of the orbiter at main engine cutoff. This is shown in Figure 11. As can be seen, the insertion energy increases with apogee for the retro system and also for OTO using Pacific Ocean disposal of the ET, although the energy is slightly less for OTO. Recall that OTO Pacific Ocean disposal cannot be effected for apogees less than ~ 200 NM because of excessive ET impact dispersions.

However, for apogees less than 200 miles, where OTO disposal must be into the Indian Ocean, the energy of the vehicle at main engine

24

FIGURE 11

ENERGY AT MAIN ENGINE CUTOFF

APOGEE OF INSERTION CONIC (N. M.)
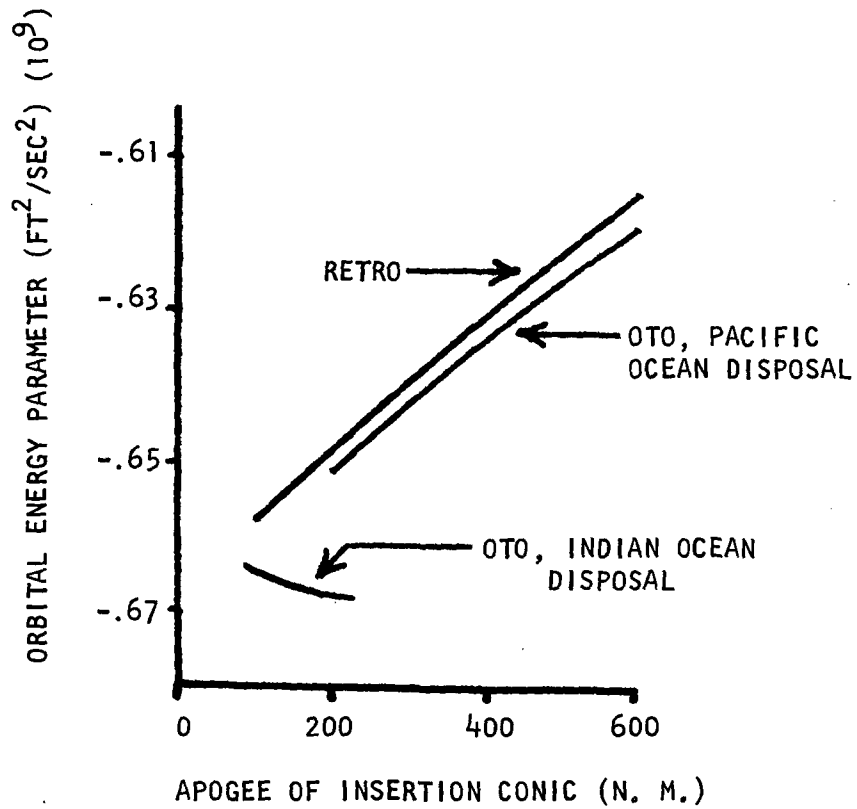
cutoff _decreases_ with increasing apogee. This behavior is in turn
explained by reference to Figure 12 , which shows the perigee of
the insertion conic as a function of the apogee. For the retro system,
the perigee is constant; hence, as apogee is raised, the energy does
increase. For Pacific Ocean disposal, OTO, the perigee is always
above the surface of the earth and ranges from around 40 to around
25 NM for apogees from 200 to 600 NM. These perigees are only slightly
below those for the retro system and energy also increases with apogee.

However, for Indian Ocean disposal, the perigee decreases very
rapidly as apogee is raised, resulting in a net loss in orbital energy
with increasing apogee. This difference in behavior is explained by
considering the impact range angle from main engine cutoff for Indian
disposal ($<180^{\circ}$) and Pacific disposal ($<270^{\circ}$). For Pacific disposal,
even if injection is close to perigee, the tank is coming around
approaching perigee again as it approaches the desired impact range
and has a shallow flight path angle through the atmosphere, so the
atmosphere can be used to effect capture for Pacific disposal.
However, for Indian disposal, the range angle is sufficiently short
that, unless injection occurs fairly close to apogee, perigee will
be at too large a range angle to permit atmospheric capture and the
orbit characteristics must be such as to insure capture (i.e. vacuum
impact, although not necessarily at the desired range). Total weight
at main engine cutoff (cutoff weight) of the orbiter and ET vs
apogee of the insertion conic is shown in Figure 13, as is orbiter
insertion weight (cutoff weight minus ET weight). As would be expected
from the energy discussion, the retro system and OTO Pacific disposal
have essentially the same cutoff weight, Pacific disposal falling off
slightly at higher apogees due to the significant positive flight path
angle at injection. OTO with Pacific Ocean disposal shows about 4000
pounds more injection weight for the same vehicle, due to the re-
moval of the 4000 pound retro system. OTO with Indian Ocean disposal
shows the largest cutoff and injection weights due to the lowered
energy requirements at main engine cutoff. The loss of cutoff weight
with increasing apogee is again due to the increasing flight path
angle. Note that insertion weight is not the weight in the desired
final orbit, but is the weight in the intermediate conic achieved
by the main engine burn. The effect of OMS system performance in
transferring from the intermediate conic to the desired final orbit
must now be considered.

C. Comparison of OMS ΔV requirements and net payload (OTO vs
Retro and direct insertion vs standard insertion)

OMS ΔV requirements vs circular final orbit altitude are shown in
Figure 14.

For the standard insertion technique via an intermediate transfer

26

FIGURE 12
PERIGEE OF INSERTION CONIC
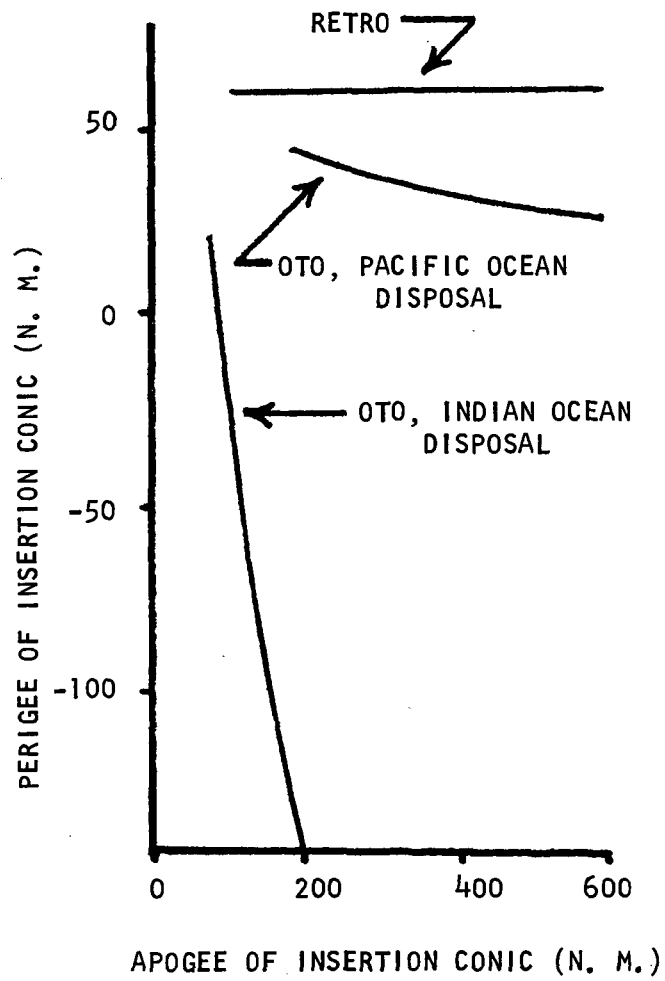

RETRO

50

OTO, PACIFIC OCEAN
DISPOSAL

0

OTO, INDIAN OCEAN
DISPOSAL

-50

-100

PERIGEE OF INSERTION CONIC (N. M.)

0   200   400   600

APOGEE OF INSERTION CONIC (N. M.)

27

FIGURE 13

ASCENT PERFORMANCE COMPARISON

28

FIGURE 14
OMS ΔV REQUIREMENTS

OMS-TO-ORBIT (OTO)

RETRO

OTO
PACIFIC OCEAN
DISPOSAL

RETRO

OTO
INDIAN OCEAN
DISPOSAL

ORBIT ALTITUDE (N.M.)

OMS ΔV (FPS)

- - - VIA INTERMEDIATE
TRANSFER ORBIT
(BASELINE
TECHNIQUE)

——— INSERTION INTO
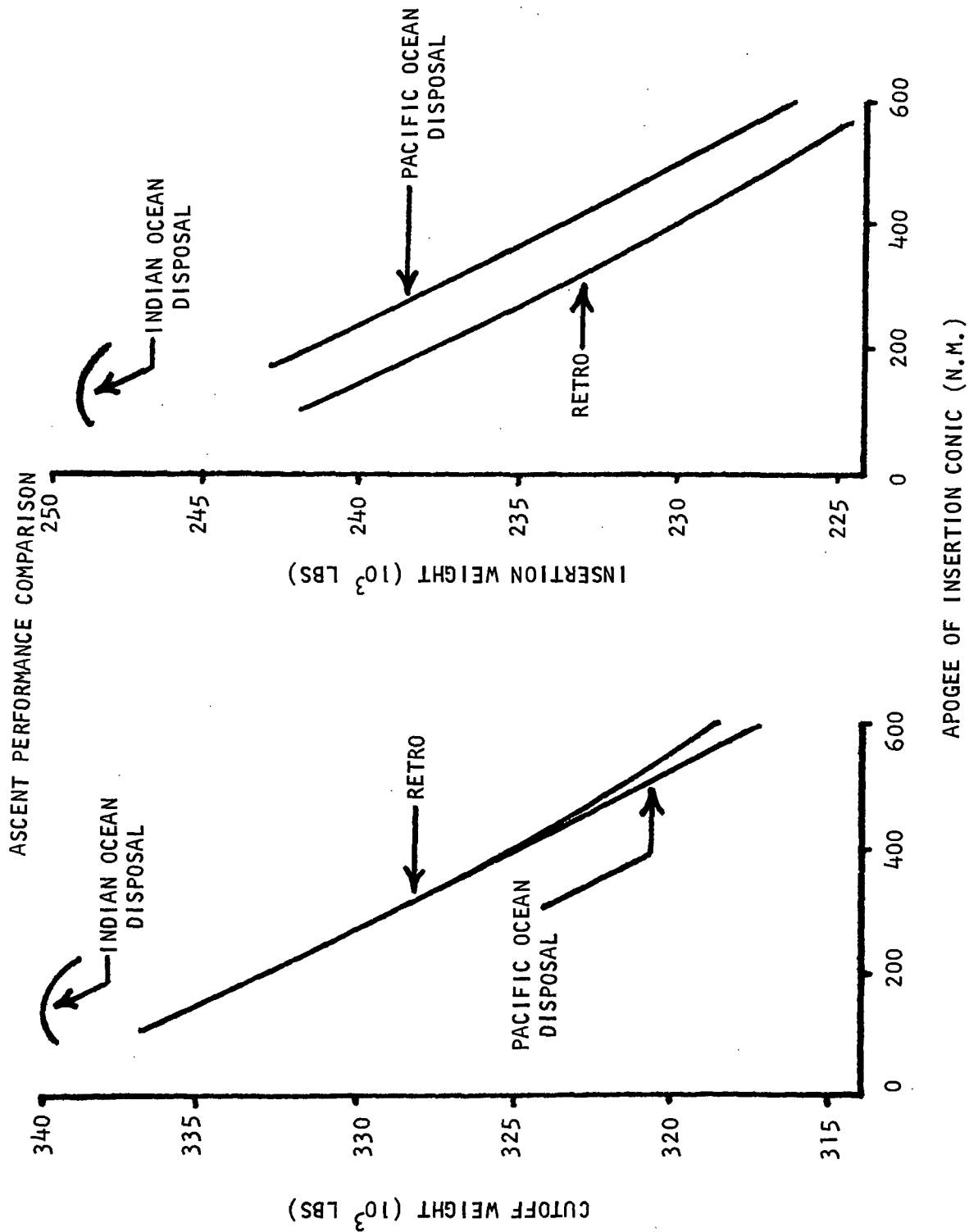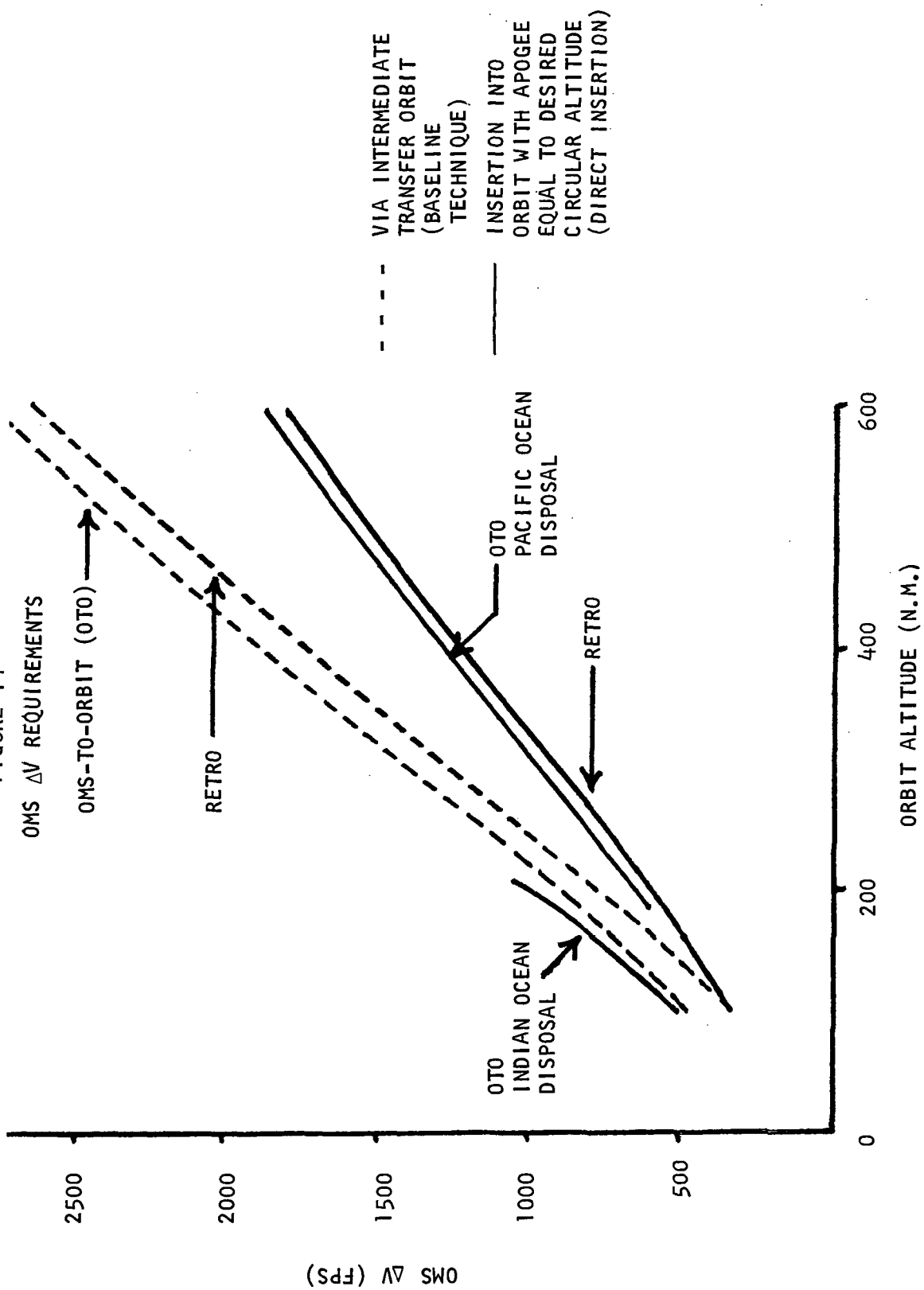ORBIT WITH APOGEE
EQUAL TO DESIRED
CIRCULAR ALTITUDE
(DIRECT INSERTION)

29

ellipse, the orbiter with an ET retro system is inserted into a 60 x 100 NM orbit by the main engines. The OMS must raise perigee to 100 NM, raise apogee to the desired operating altitude, circularize and deboost after the mission is completed. For OTO, insertion to effect the desired ET disposal is into a (typically) 13 x 80. The OMS system must first raise apogee to 100 NM and then go through the same sequence as described above for the retro system. The raising of apogee and extra ΔV to raise perigee further causes a ΔV penalty of 140 fps for OTO over retro, as shown on Figure 14 . This number (140 fps) incidentally, appears sensitive to the ET impact point in the Indian Ocean and may be able to be lowered with further study.

For direct insertion, in which main engine cutoff occurs in a conic with apogee equal to the desired orbit altitude, all the OMS must do is raise perigee and subsequently deboost. Unless one has some unusual flight mechanics, this should result in a lowered OMS ΔV requirement, as demonstrated by the retro and OTO Pacific drop direct insertion cases shown again on Figure 14 . The OTO Pacific drop ΔV is from 30 to 60 fps higher than for the retro system, reflecting the need to raise perigee an extra 20 to 35 NM.

The unusual flight mechanics case is shown by direct insertion with Indian Ocean disposal. The insertion orbit with an apogee of 200 NM has less energy than the baseline orbit. Thus even though one has to do less maneuvers for direct insertion, one has to make up more orbital energy to circularize at 200 NM from the orbit with that apogee than by going through the standard sequence. The net result is that it takes less ΔV to get there via the baseline method than via direct insertion.

Using Figures 13 and 14 the maximum net round trip payload (including OMS kit inert weight) vs orbit altitude is shown in Figure 15. The main message of this figure is that except for OMS kits inert weight differences, the PL weight is essentially the same for the standard insertion technique and direct insertion. Hence, direct insertion's primary advantages, if there are any, must come from the OMS ΔV savings in Figure 14.

A second point from Figure 15 is that OTO does have significant payload advantages (1000-3000 pounds) over the retro system for the same shuttle.

D. Comparison of OMS propellant requirements

Using Figures 13 and 14, the OMS propellant weight requirements are shown in Figure 16. A small portion of the extra OMS requirements for OTO compared to the analogous retro case comes from the extra payload weight, but most of it comes from the extra ΔV requirements
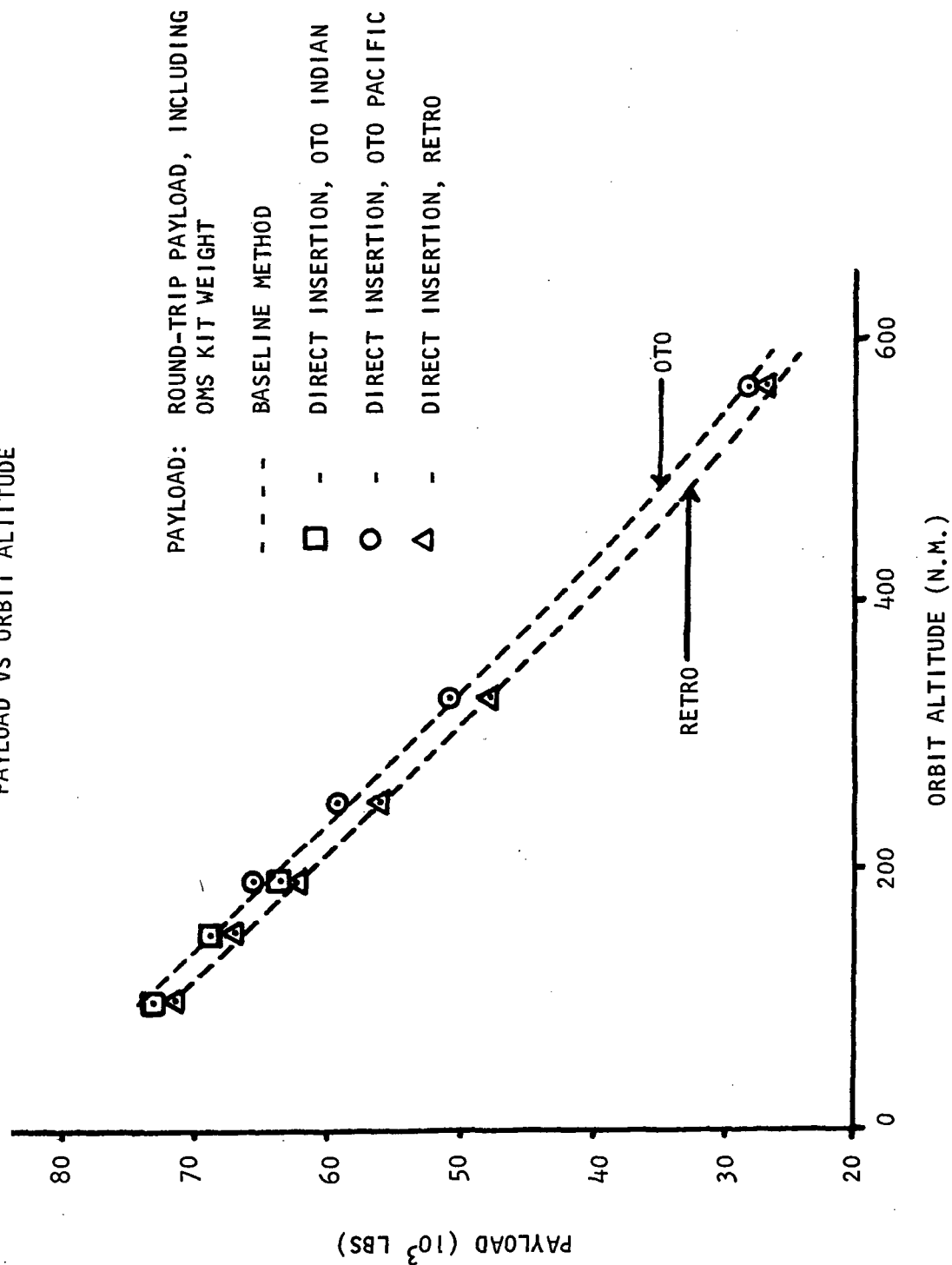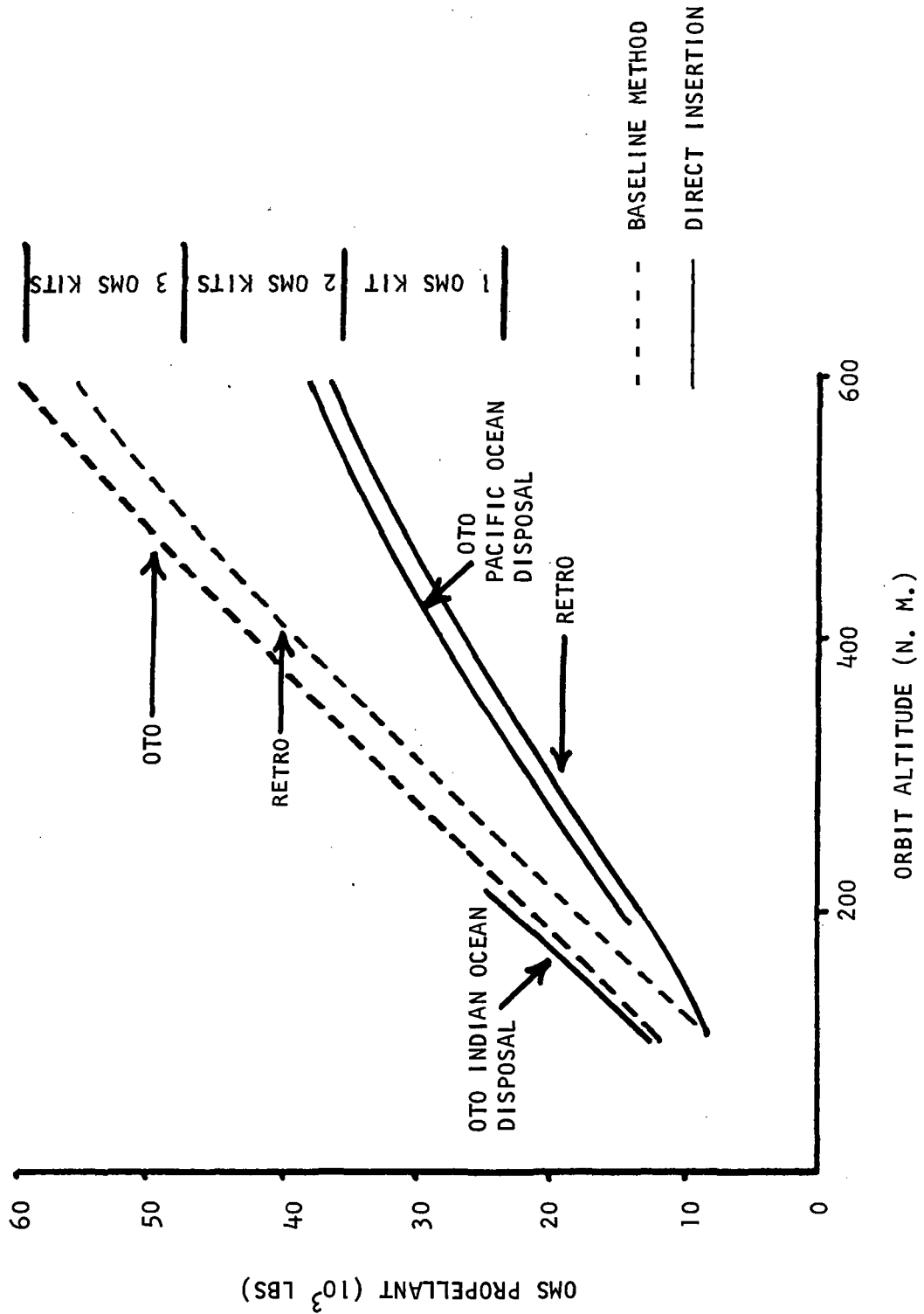
FIGURE 15

PAYLOAD VS ORBIT ALTITUDE

FIGURE 16

OMS PROPELLANT - MAXIMUM PAYLOAD

32

shown on Figure 14.

The extra OMS propellant requirement means that an OMS kit must be added sooner (at a lower orbit altitude) for OTO than for retro. The orbit altitude at which the first OMS kit must be added for each of the systems and injection methods considered are shown in the table below. Two altitude values are shown for each case, corresponding to (1) maximum payload, and (2) zero payload (service mission).

ORBIT ALTITUDES WHERE FIRST OMS KIT
MUST BE ADDED

MAXIMUM PL/ZERO PL

	RETRO	OMS-TO-ORBIT
BASELINE INSERTION	255/320	220/290
DIRECT INSERTION	360/445	335/430

As may be seen, it is necessary to add an OMS kit from 15 to 35 NM sooner with OTO than for retro, depending on the payload and the insertion method.
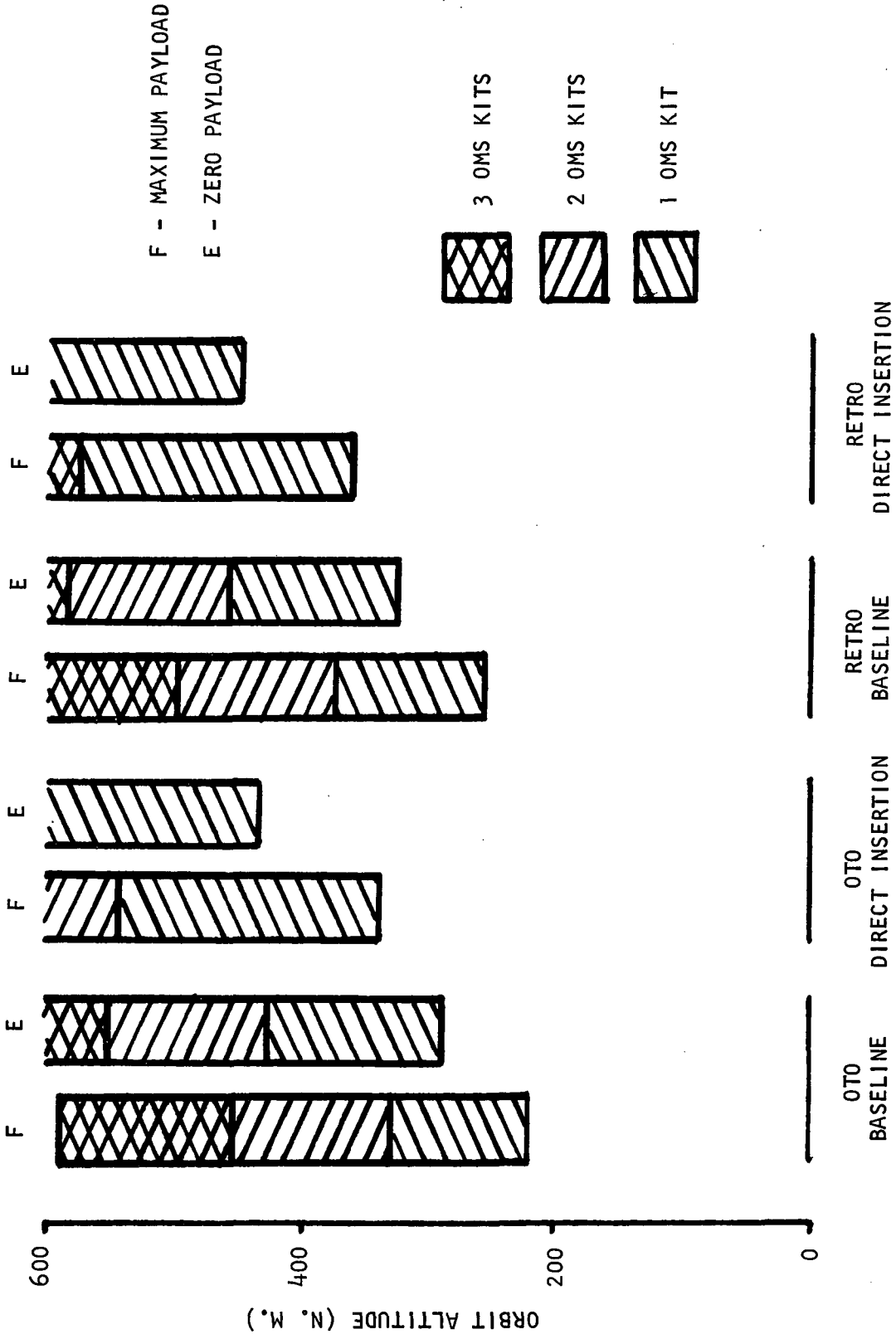
The significance of this is that the OMS kits occupy 12.3 feet of the payload bay. Thus at the time the first OMS kit is introduced, the payload bay is effectively reduced from 60 to 47.7 feet in length.

The primary advantage of direct insertion now becomes clear-- it delays payload bay reduction by 105 to 140 NM, depending on payload, insertion technique, and ET disposal technique.

The primary disadvantage of OTO for the payload user also lies in this same area--volume reduction occurs at 15 to 35 NM lower altitudes. The significance of this depends on the traffic model.

The altitudes at which the first OMS kit must be added are shown graphically in Figure 17 , along with the altitudes at which the second and third kits must be added. The same trends are shown for the other kits as for the first kit.

FIGURE 17

NUMBER OF OMS KITS VERSUS ORBIT ALTITUDE

F – MAXIMUM PAYLOAD

E – ZERO PAYLOAD

3 OMS KITS

2 OMS KITS

1 OMS KIT

RETRO
DIRECT INSERTION

RETRO
BASELINE

OTO
DIRECT INSERTION

OTO
BASELINE

ORBIT ALTITUDE (N. M.)

600

400

200

0

34

Having this OMS kit information we can now go back and refine the payload comparison data shown on Figure 15 . As a typical example, the net payload gain, including effect of OMS kit inert weights, for direct insertion over the standard insertion technique for the OTO system is shown in Figure 18.

Notice first that direct insertion for apogees less than 200 NM, for which disposal must be in the Indian Ocean results in a payload loss . Since it also requires more OMS propellant (Figure 16), direct insertion has no obvious advantages over the baseline insertion technique for apogees less than 200 miles for OTO ET disposal.

The rather strange curve for Pacific Ocean disposal can be explained as follows. Initially, for altitudes less than 220 NM, neither insertion method requires an OMS kit. In this range, direct insertion has an inherent payload advantage of around 400 pounds. At 220 NM, one would have to add the first OMS kit, with an inert weight of around 1800 pounds. Since no OMS kit is required for direct insertion, direct insertion picks up an additional relative payload gain of 1800 pounds for a total payload gain of 2200 pounds . At about 330 N.M. altitude, one would have to add a second OMS kit using the standard insertion technique, with an inert weight of 1230 pounds, giving direct insertion a payload benefit of around 3400 pounds. However, at essentially the same altitude, using direct insertion, one would have to add the first OMS kit, reducing its advantage by 1800 pounds for a net advantage at around 1600 pounds. The next discontinuity occurs at 455 NM, when one must add a third kit using the standard insertion technique, and the next (negative) discontinuity at 540 NM, when one must add a second OMS kit for direct insertion.

E.   Summary performance comparison of insertion methods

As a result of determining the performance effects over a range of payloads, a summary comparison of performance-altitude capability is presented in Figure 19 for OTO direct insertion versus the OTO baseline ascent method. The dashed lines are for direct insertion. The most significant information on the figure is the lines which indicate the points at which the first OMS kit is added, hence where the payload bay length is shortened for each ascent method. Notice that direct insertion permits the accommodation of long payloads which have altitudes above the baseline first-OMS-kit-added line but below the direct insertion first-OMS-kit-added line. Thus direct insertion buys the additional long-payload capability represented by the area between the two lines, at the price of tank disposal in the Pacific Ocean.

FIGURE 18

PAYLOAD GAIN FOR DIRECT INSERTION VERSUS BASELINE INSERTION (OTO SYSTEM)
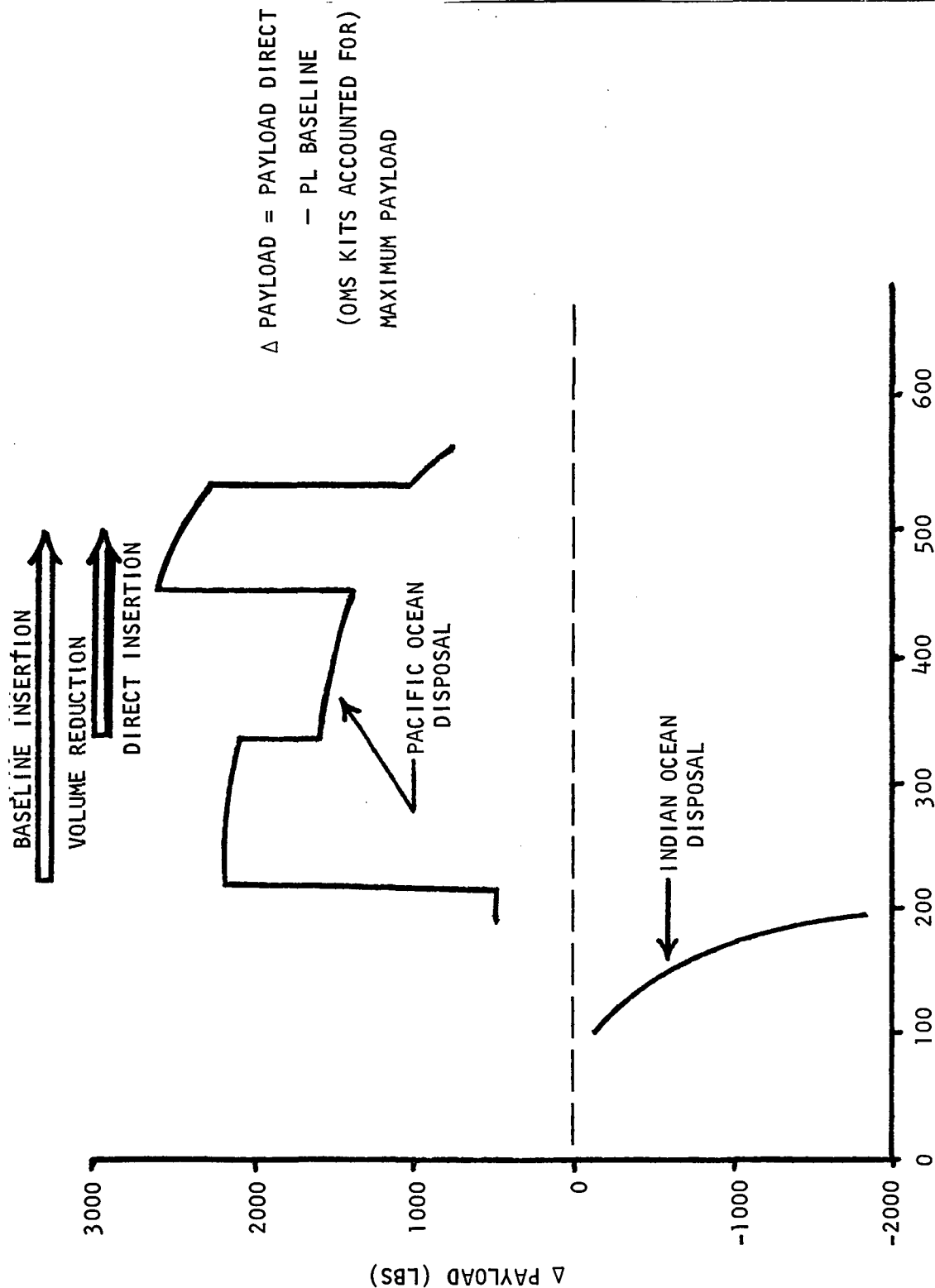
36

FIGURE 19

PAYLOAD - ALTITUDE CAPABILITY
DUE - EAST LAUNCH

——— BASELINE INSERTION
(INDIAN)

――― DIRECT INSERTION
(PACIFIC)

NO DIRECT INSERTION BELOW 200 N. M.

PL BAY REDUCED TO 47.7 FT. WHEN
FIRST OMS KIT ADDED

FIRST OMS KIT ADDED - DIRECT INSERTION

FIRST OMS KIT ADDED - BASELINE INSERTION
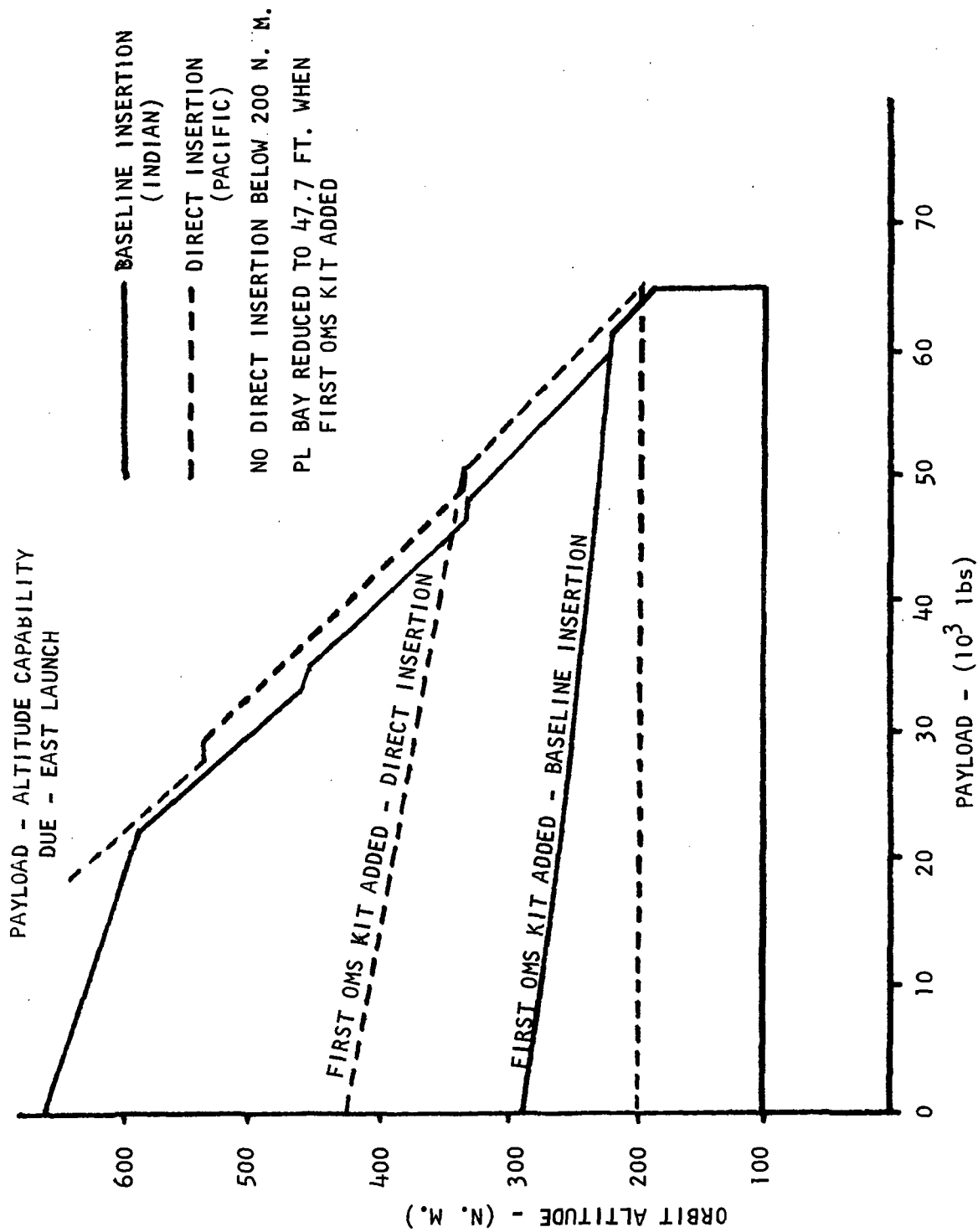
ORBIT ALTITUDE - (N. M.)

PAYLOAD - (10^3 lbs)

37

F. Performance Analysis Conclusions

Conclusions drawn from the performance analysis may be categorized according to which issue is addressed: OMS-to-orbit versus retro disposal or direct insertion versus baseline ascent method.

1. Regarding OMS-to-orbit versus retro disposal:

a. OMS-to-orbit yields somewhat better payload performance than retro disposal - primarily because of the reduction in tank weight achieved by eliminating the retro system.

b. However, because of the higher OMS propellant demand of OTO, the OTO method requires the addition of OMS kits (and hence reduced payload bay length) for a slightly lower orbital altitude than does retro disposal. This small difference (~35 N.M.) is not significant.

c. For OTO, direct insertion to higher altitudes requires much more OMS energy for Indian Ocean disposal than for Pacific Ocean disposal. This forces the use of Pacific Ocean disposal for OTO high orbit cases in a manner analogous to the way in which retro rocket size requirements forces the use of Pacific disposal for retro high orbit cases.

2. Regarding direct insertion versus baseline ascent method (assuming OTO):

a. For altitudes below 200 N.M., direct insertion shows no advantage, because Indian Ocean disposal is required, with its attendant performance loss.

b. For altitudes above 200 N.M., direct insertion shows a slight payload advantage (500-2500 pounds), as indicated in Figure 19.

c. The major advantage of direct insertion lies in providing additional altitude capability before the payload bay length is reduced by the addition of OMS kits. The added altitude capability ranges from 110 to 130 N.M., depending on payload, as shown in Figure 19.

d. The main disadvantage of direct insertion is the requirement for tank disposal in the Pacific Ocean, with its higher ship and airplane densities.

IV. Recommendations

A. The Shuttle system design strongly favors OTO passive disposal for the external tank. This study has shown that even from a payload accommodation viewpoint the retro disposal concept has little advantage and significant disadvantages. Therefore, it is recommended that the retro disposal concept be allowed to rest in peace.

B. Considering the desire for standardization of Shuttle mission operation procudures, baseline insertion with Indian Ocean disposal should be used for all ETR missions whose altitude-length-weight requirements are compatible with the baseline capability.

C. It is recommended that direct insertion be considered as a means of accommodating long payload ETR missions having sufficient altitude that baseline insertion would require OMS kits. The benefits of accommodating such missions by direct insertion must be weighed against the higher probability of ship or airplane impact entailed by Pacific Ocean disposal. Also operational effects such as would be caused by the elimination of a parking orbit should be assessed.

D. Direct insertion for WTR missions should be investigated. Preliminary indications are that the geography and geometry associated with WTR missions are not easily compatible with direct insertion.

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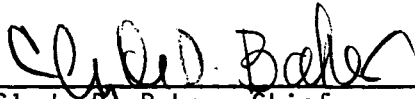
EFFECTS OF ASCENT TRAJECTORY MODE AND TANK DISPOSAL METHOD ON SHUTTLE PAYLOAD ACCOMMODATION
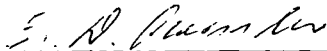
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